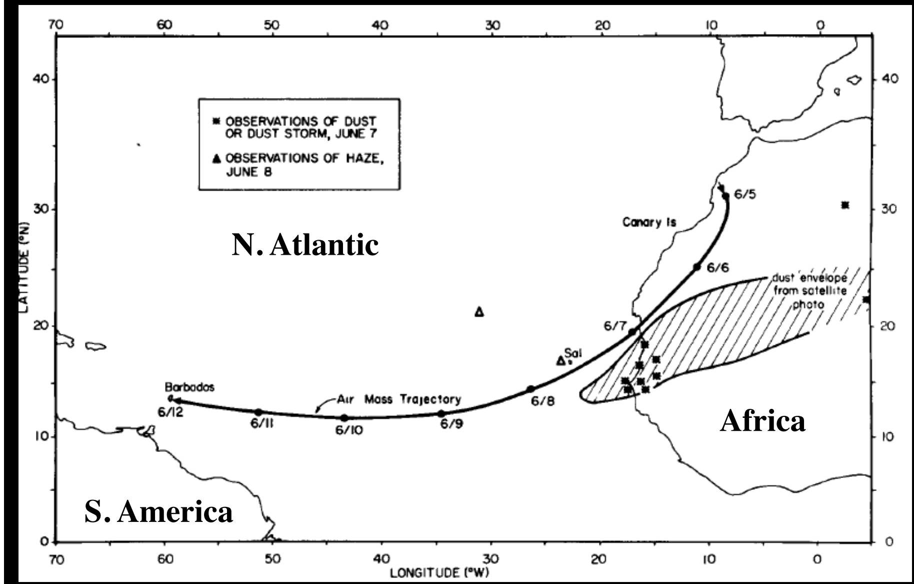
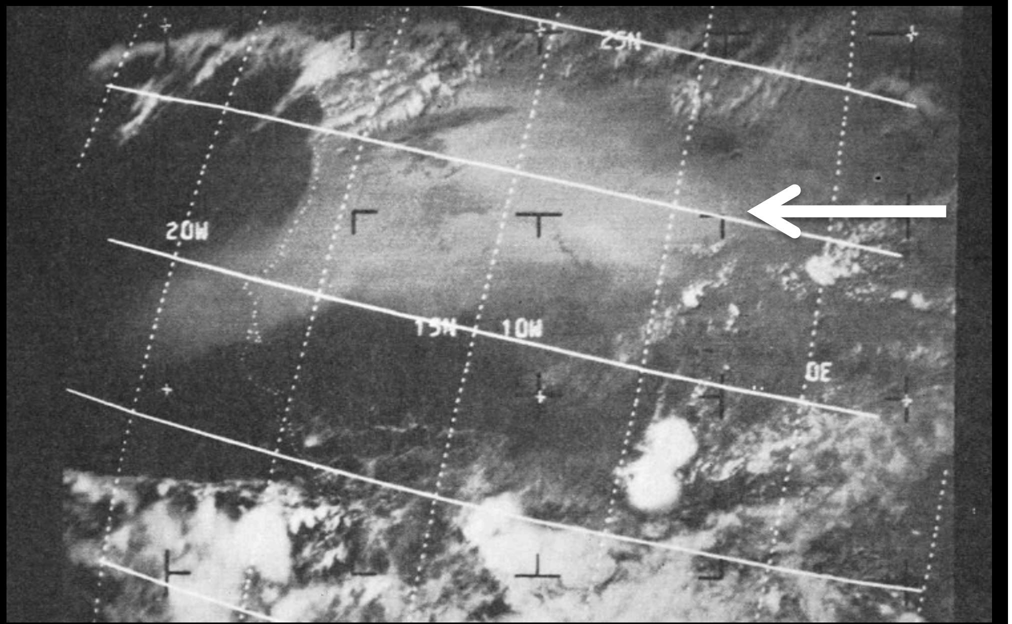
More Than the Sum of the Parts: Satellite Aerosol Remote Sensing, and Its Relationship to Sub-orbital Measurements and Models

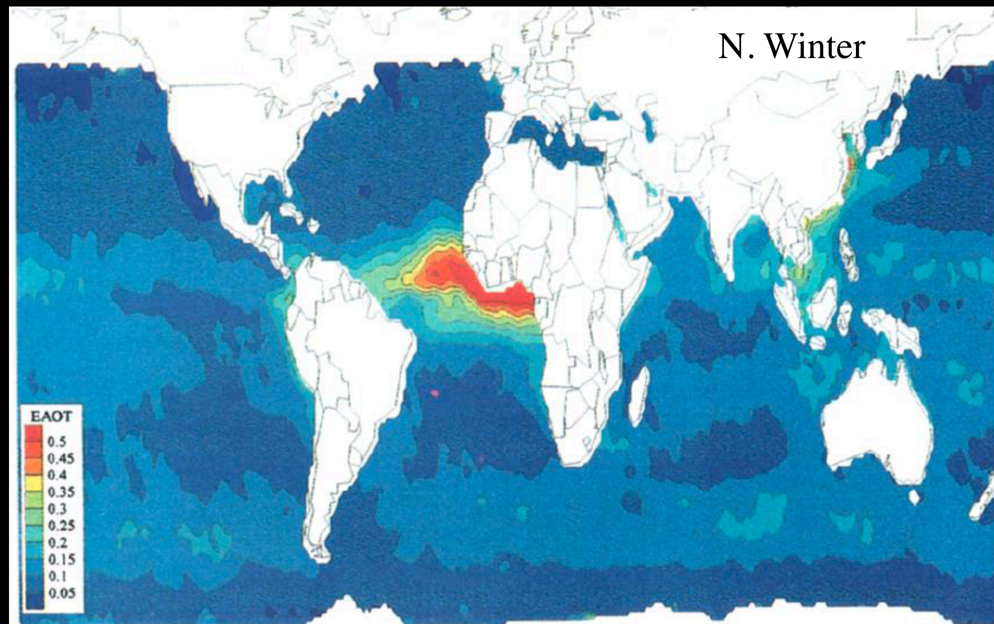
Ralph Kahn
NASA/Goddard Space Flight Center

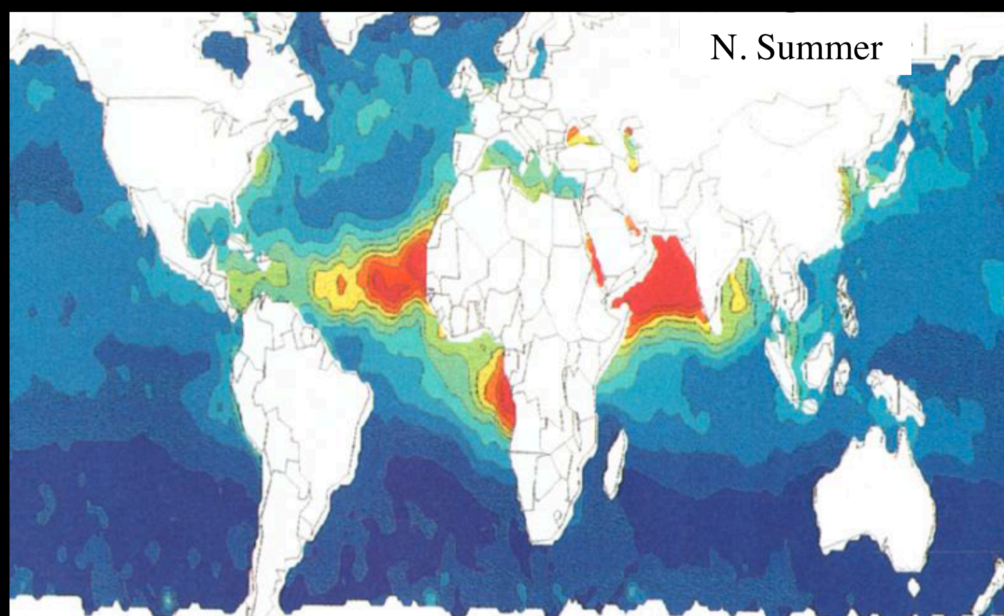




Saharan Dust Storm
8-day trajectory
Beginning 07 June 1967
ESSA 5 Satellite

Prospero et al., Earth & Planet. Sci. Let. 1970





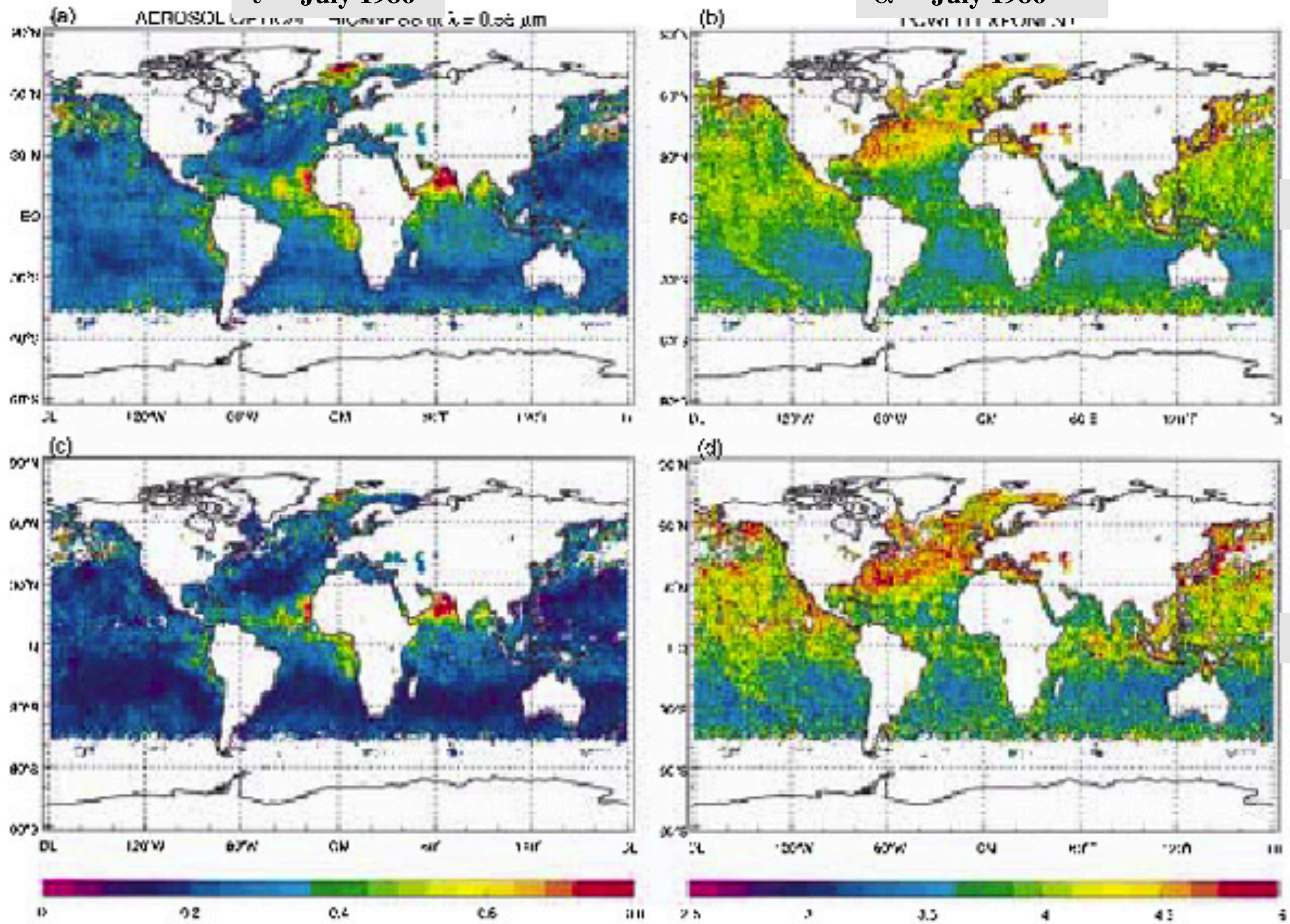
AVHRR
July 1989-June 1991
Aerosol Optical Depth

Husar, Prospero, & Stowe JGR 1997

AVHRR 2-Channel GISS AOT

τ -- July 1986

α -- July 1986

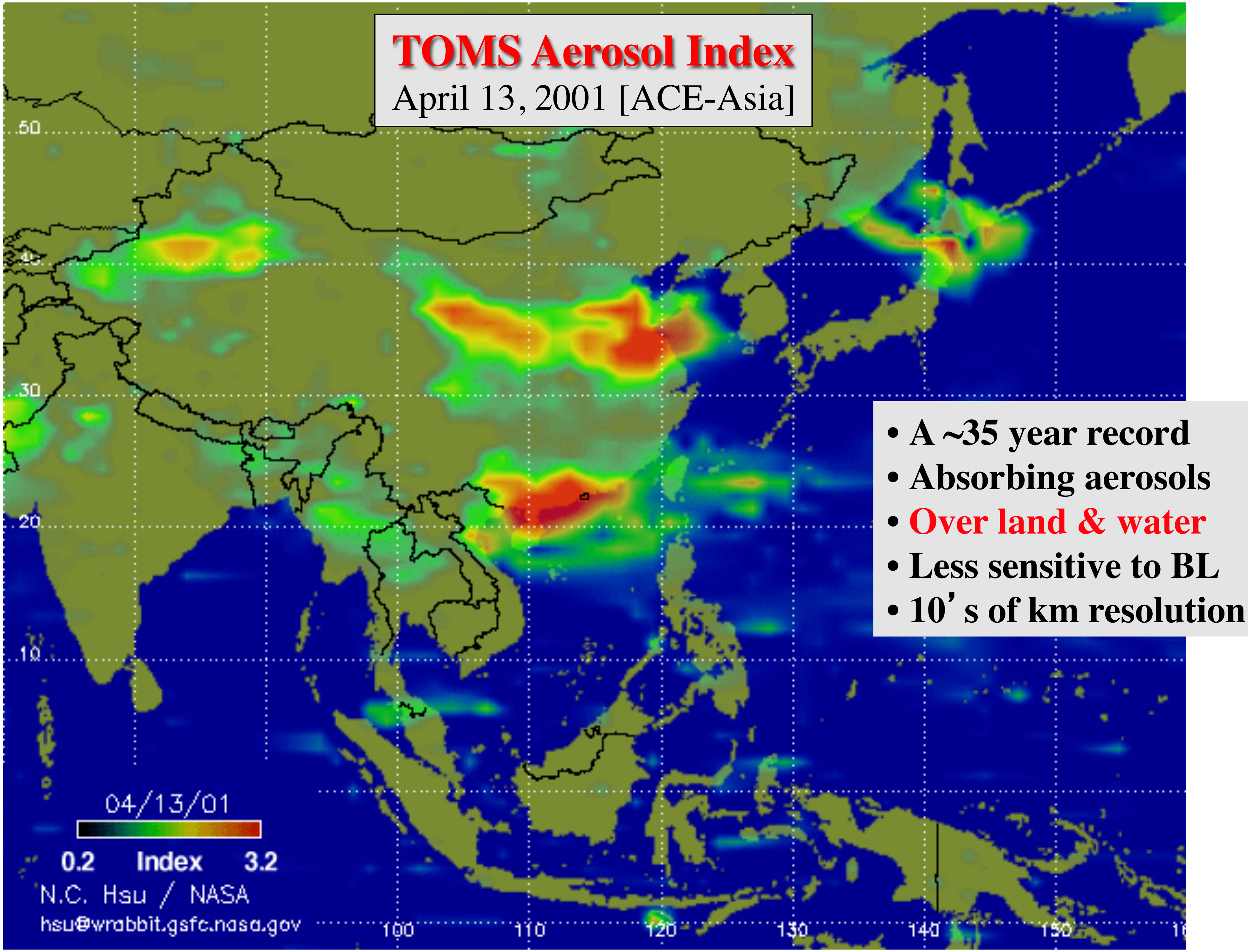


Cloud Screen 1

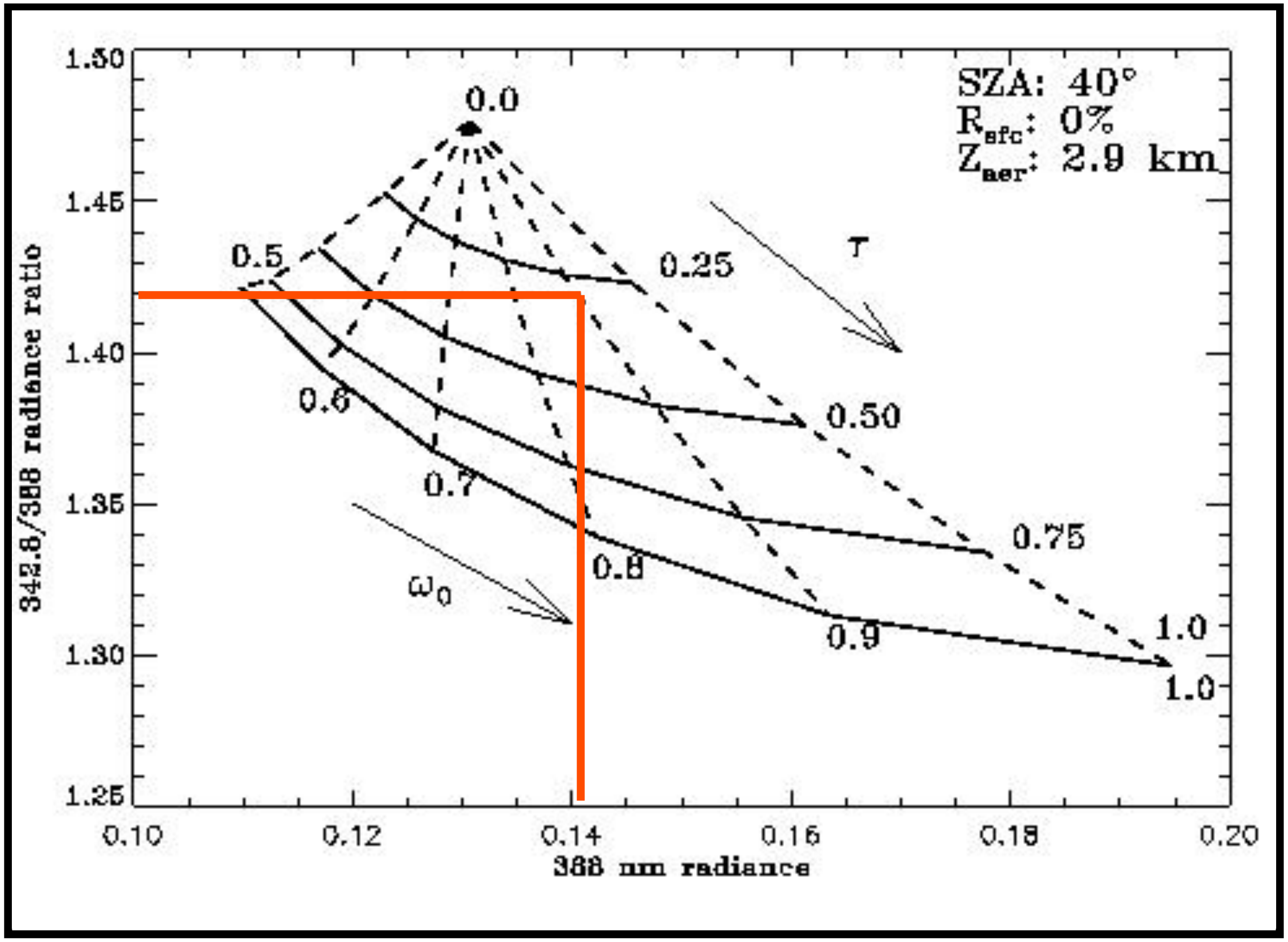
Cloud Screen 2

Fig. 6. (a) and (b) Monthly mean optical thickness (τ) and optical-thickness-weighted power exponent (α) for July 1986 derived with the benchmark atmosphere–ocean model and the standard ISCCP cloud-detection scheme. (c) and (d) As in panels (a) and (b) but with a modified cloud-detection scheme that retains only pixels with channel-5 temperatures warmer than the respective composite values.

Mishchenko et al., Appl. Opt. 1999


TOMS Aerosol Index
April 13, 2001 [ACE-Asia]
• A ~35 year record
• Absorbing aerosols
• Over land & water
• Less sensitive to BL
• 10's of km resolution
04/13/01
0.2 Index 3.2
N.C. Hsu / NASA
hsu@wrabbit.gsfc.nasa.gov
50
40
30
20
10
100
110
120
130
140
150

OMI AOT and SSA Retrieval Approach

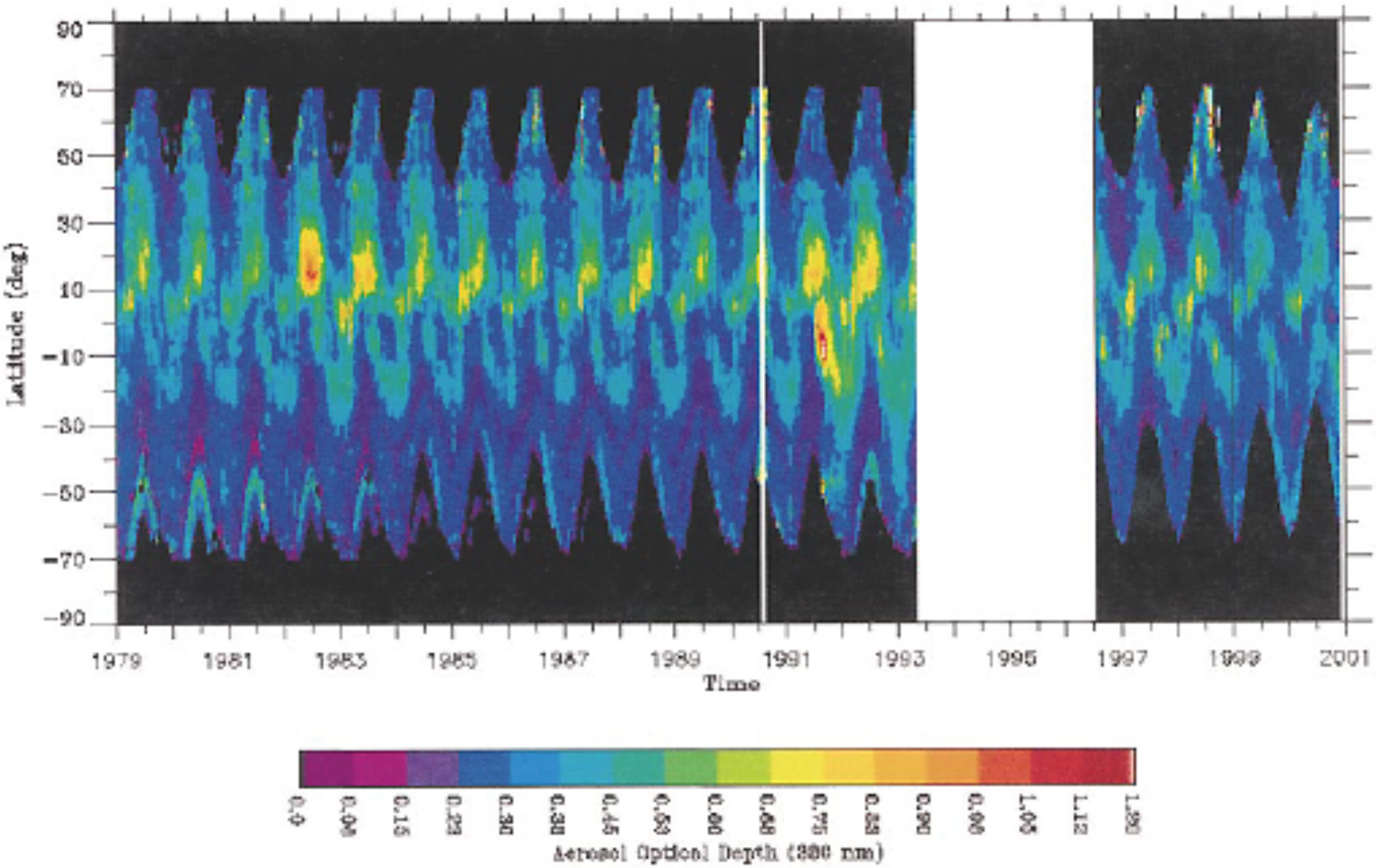


- **Aerosol reduces** the **TOA spectral contrast** of the Rayleigh-scattering gas atmosphere.
- Higher **SSA** (less absorbing) **increases the TOA** Radiance, **decreases contrast**.
- For absorbing aerosols, **elevation also matters**.
- Land **Surface** (even desert) is **usually dark** in the UV

From: Omar Torres

TOMS Aerosol Index

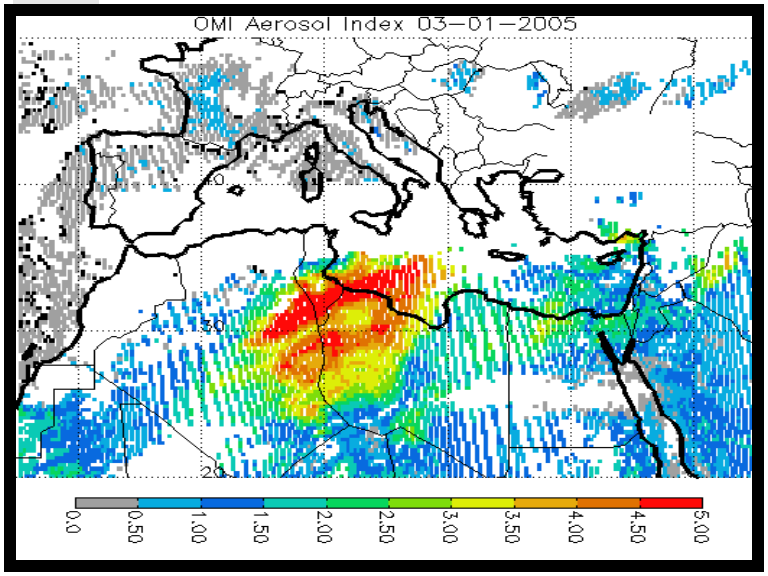
1979-2001 Weekly, Zonal, 1˚x1˚ Average Global Record



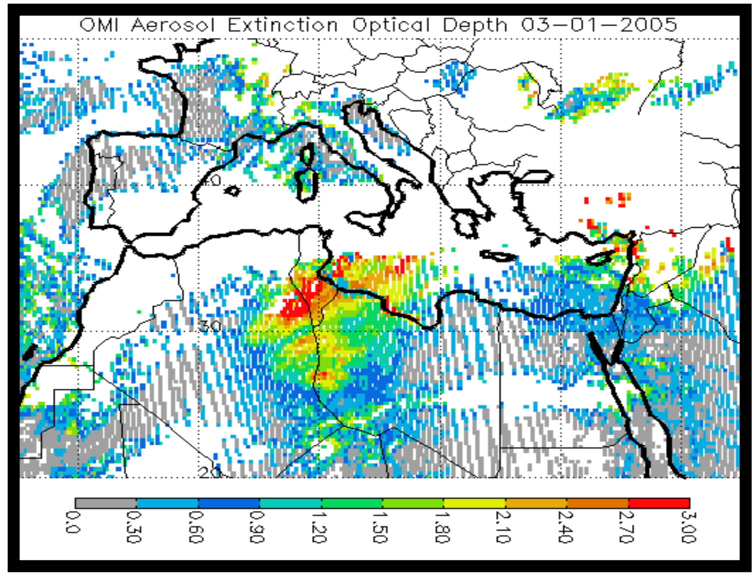
From: Torres et al, JAS, 2002

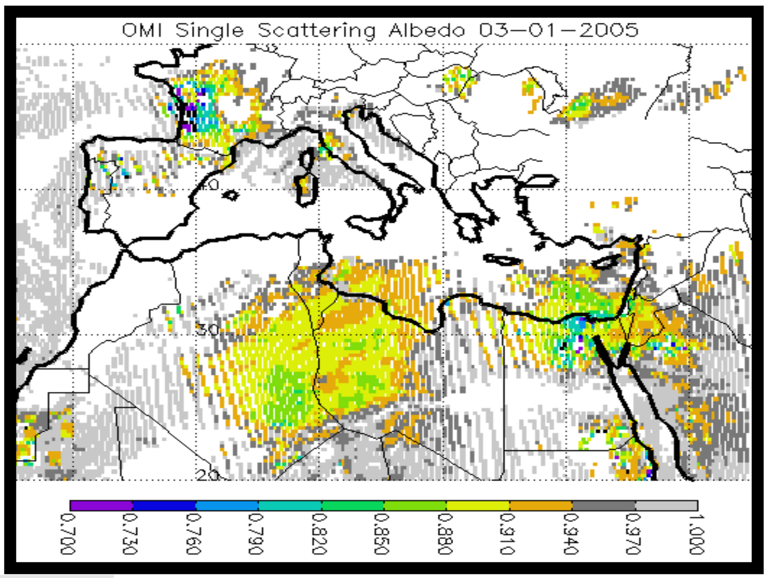
OMI Aerosol Products

AI

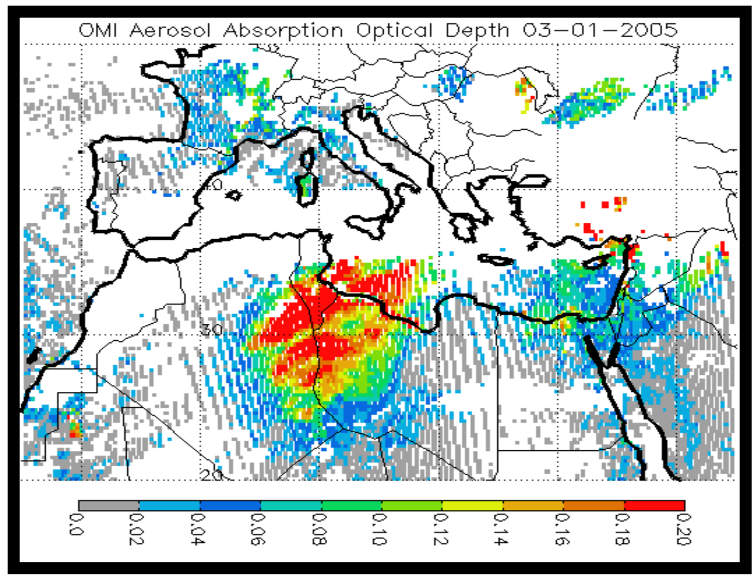


Extinction AOD





SSA



Absorption Optical Depth

March 01, 2005

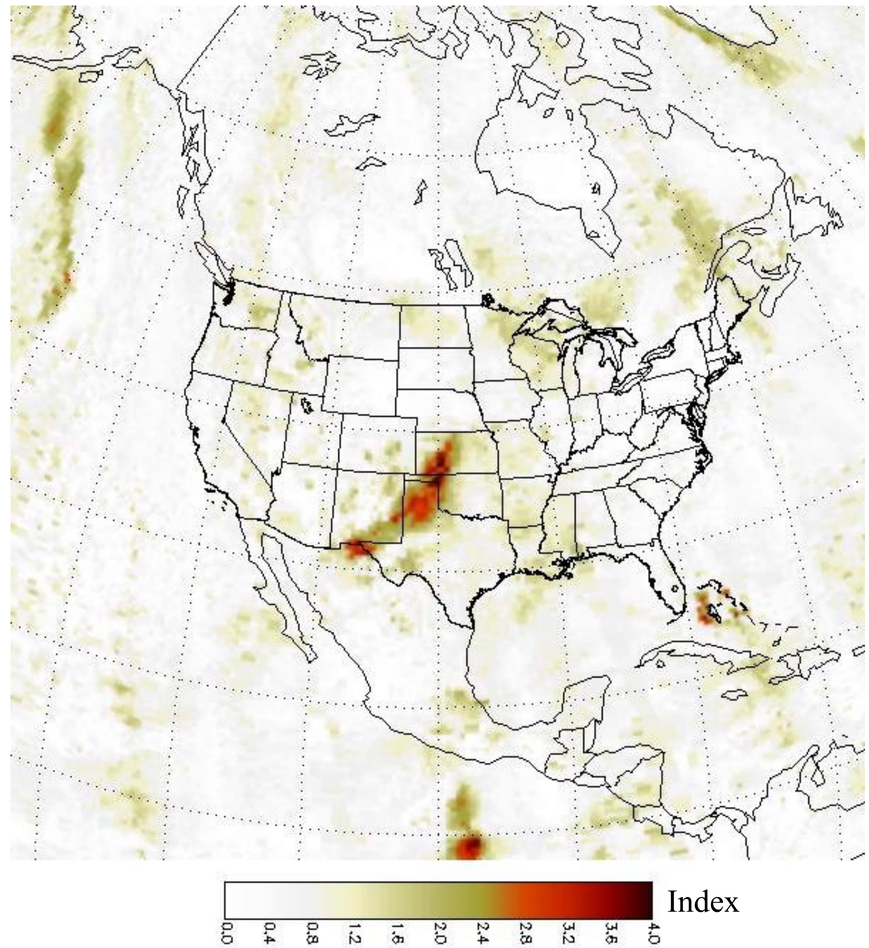
From: Omar Torres

$\color{red}{\text{OMI}}$ Products

- NO_2
- Tropospheric O_3
- Aerosol Index
- Aerosol Extinction Opt. Depth
- Aerosol Absorption Opt. Depth

<u>Note</u>: AI complements other remote-sensing aerosol products:

- Can retrieve aerosol over or mixed with cloud
- Not sensitive to small, absorbing aerosol below 2 km

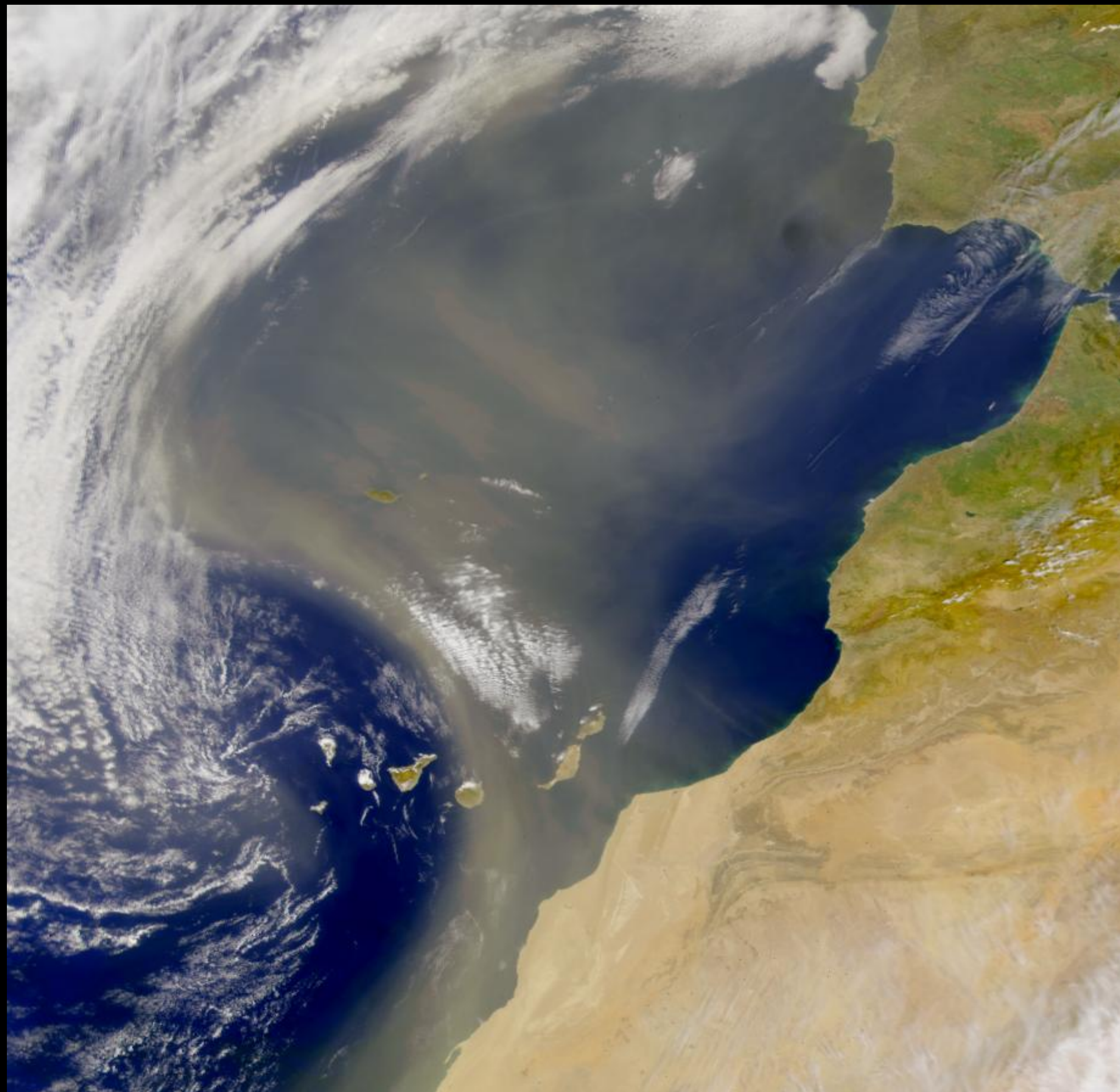


12 March 2006 Smoke over North America

From: Omar Torres/OMI Team

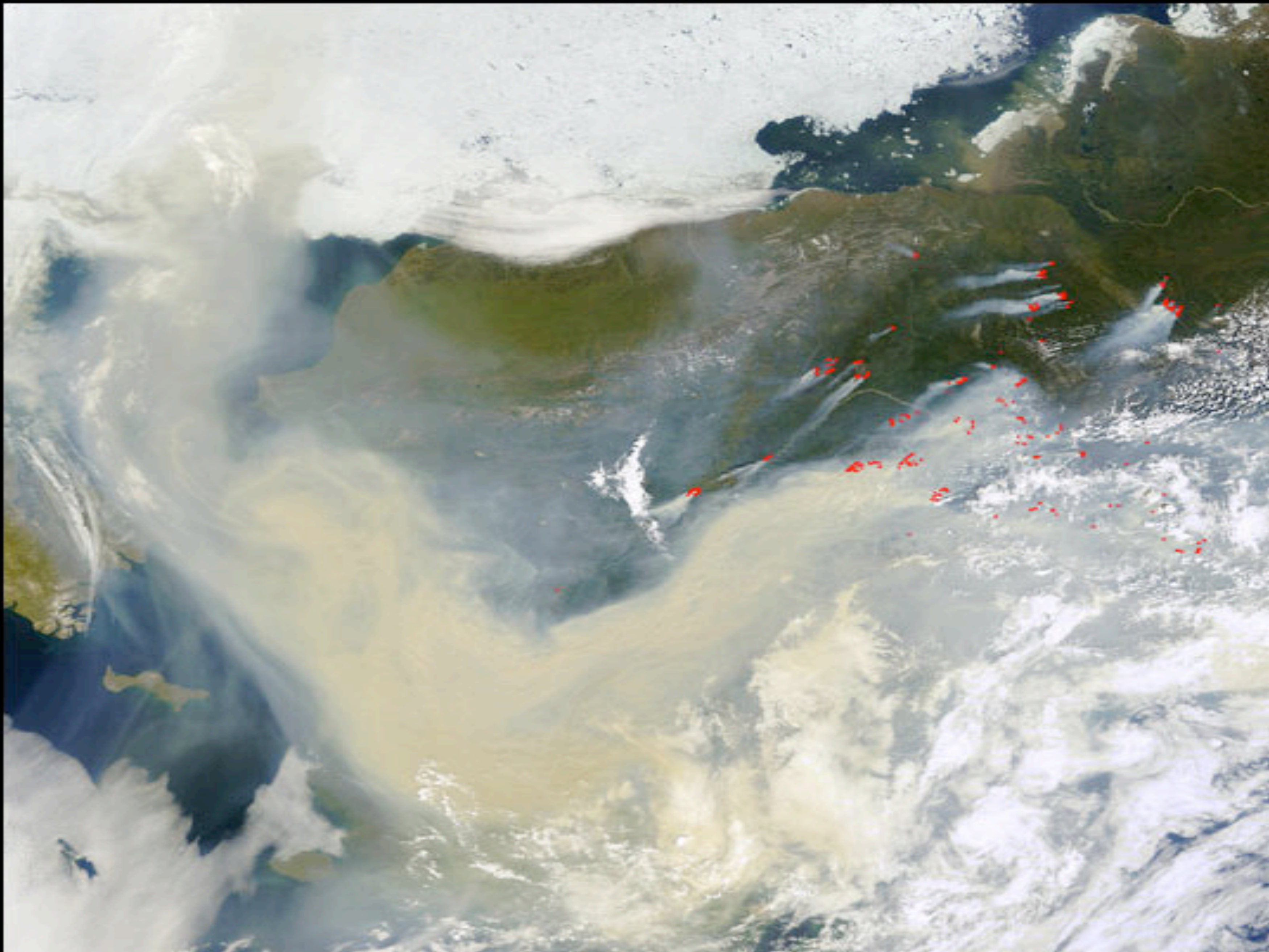
Phoenix Dust Storm 05 July 2011 Phoenix New Times

***SeaWiFS* – Sahara Dust over Canary Islands** *06 March 1998*

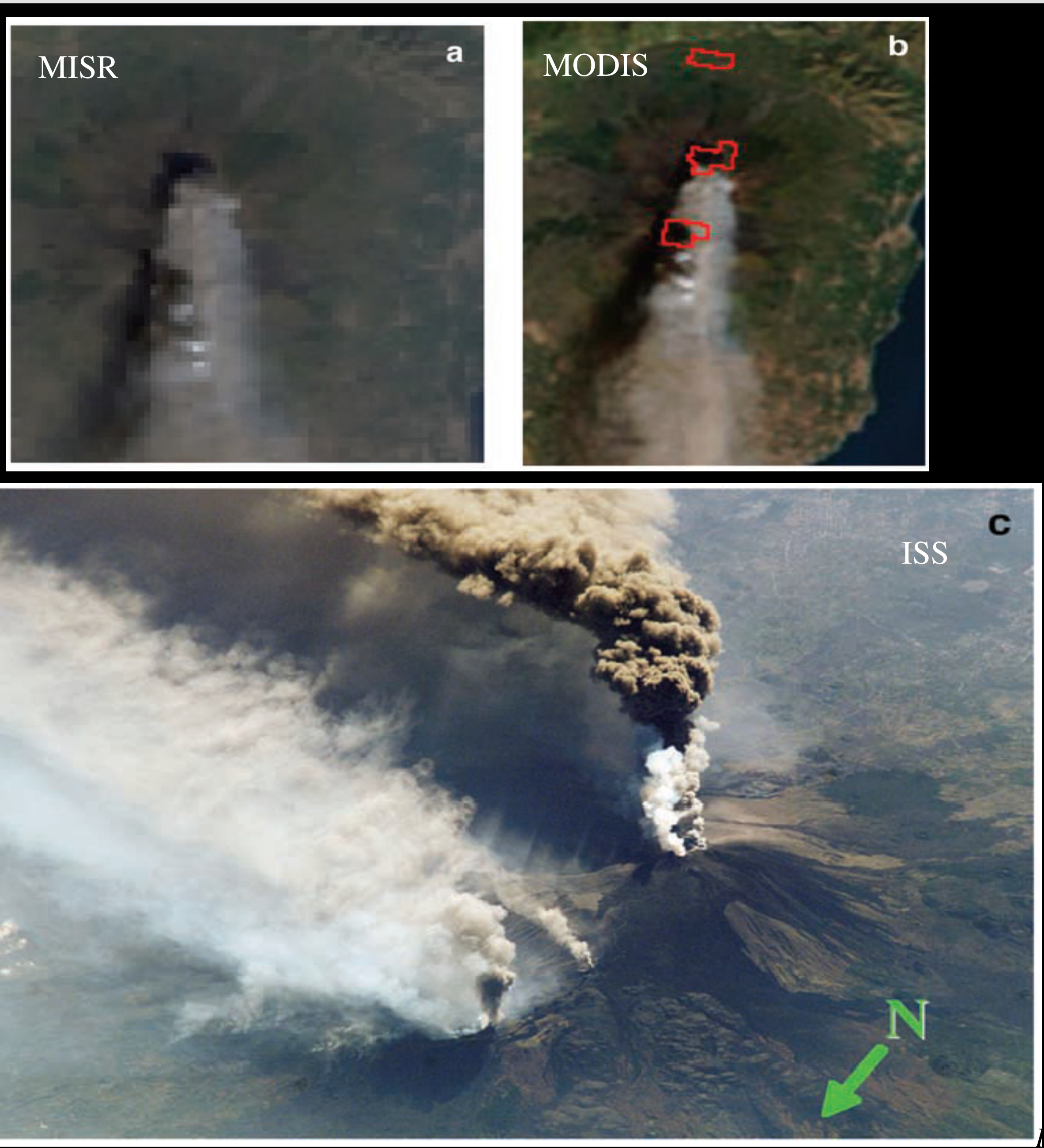



Station Fire near JPL, Pasadena CA August-September 2010
From: http://hometown-pasadena.com

MODIS – **Fires in Alaska** 01 July 2004 21:40 UTC

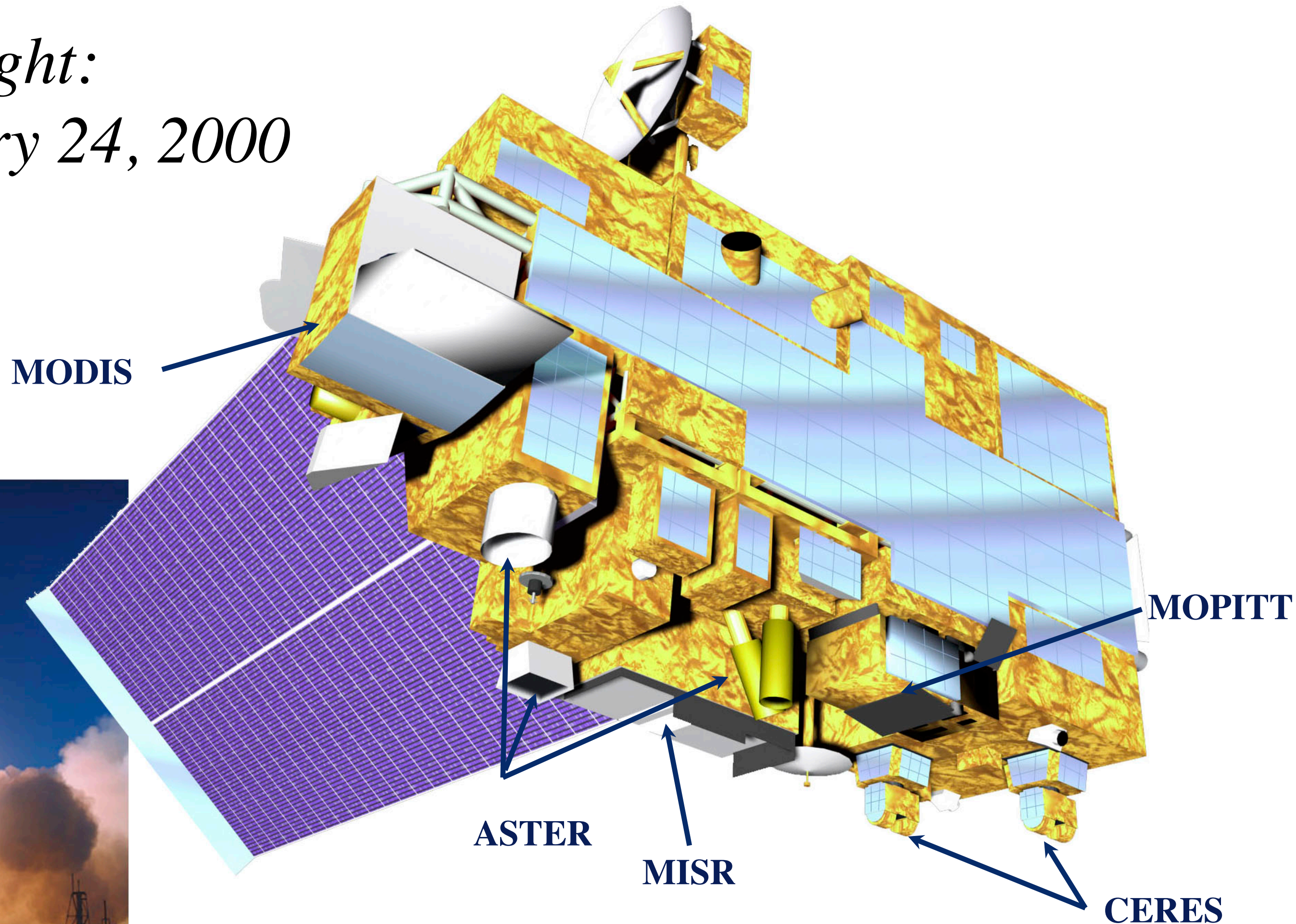


Mt. Etna Plume Structure 27-30 October 2002



The NASA Earth Observing System's Terra Satellite

First Light:
February 24, 2000



Source: Terra Project Office / NASA Goddard Space Flight Center

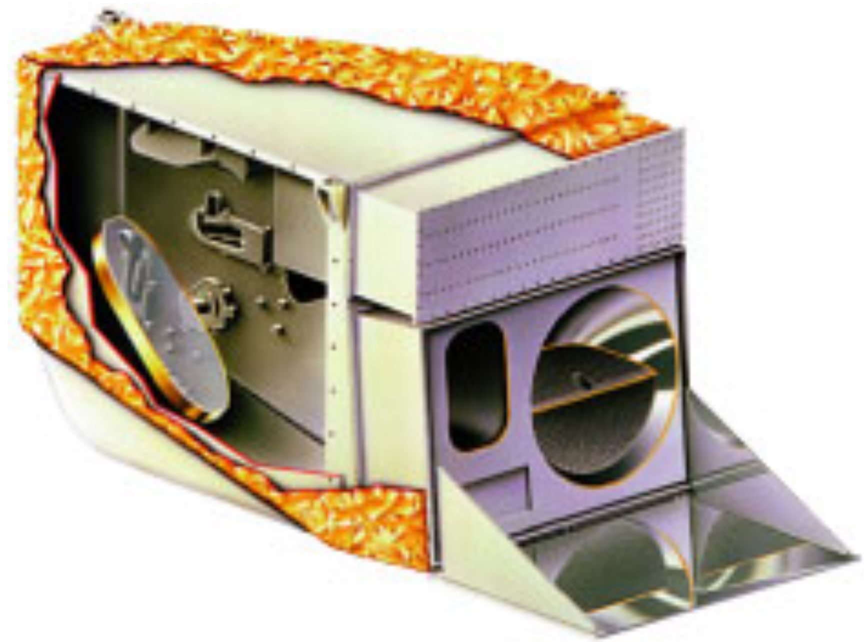
Aerosol Retrievals –

Aerosol Amount

(Optical Depth)

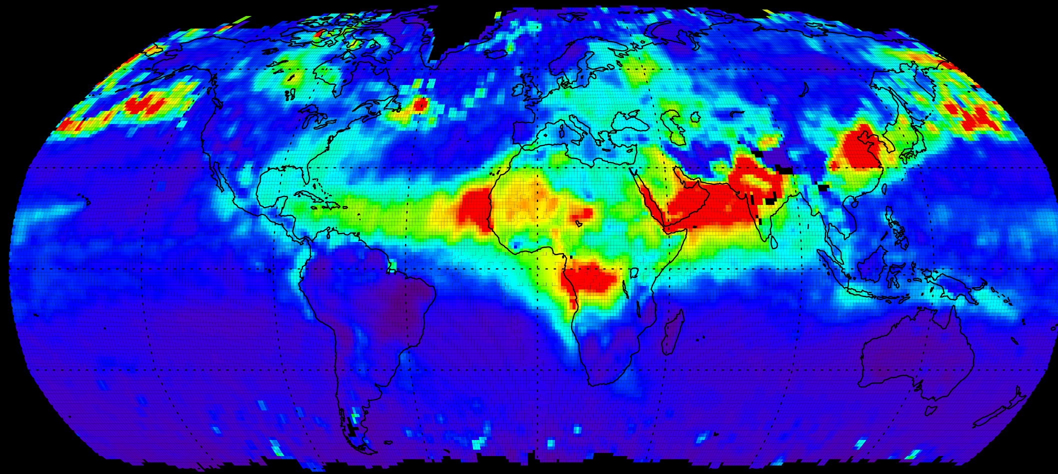
MODIS
The MODerate-resolution Imaging Spectroradiometer

- NASA, Terra & Aqua
  - launches 1999, 2001
  - 705 km polar orbits, descending (10:30 a.m.) & ascending (1:30 p.m.)
- Sensor Characteristics
  - 36 spectral bands ranging from 0.41 to 14.385 μm
  - cross-track scan mirror with 2330 km swath width
  - Spatial resolutions:
    - 250 m (bands 1 - 2)
    - 500 m (bands 3 - 7)
    - 1000 m (bands 8 - 36)
  - 2% reflectance calibration accuracy
  - onboard solar diffuser & solar diffuser stability monitor



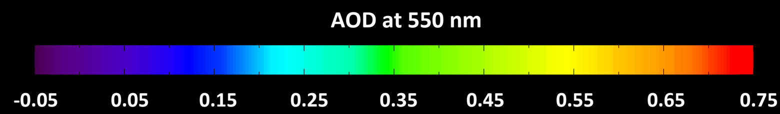
Improved over AVHRR:
- Calibration
- Spatial Resolution
- Spectral Range & # Bands

Source: MODIS Team, NASA/GSFC

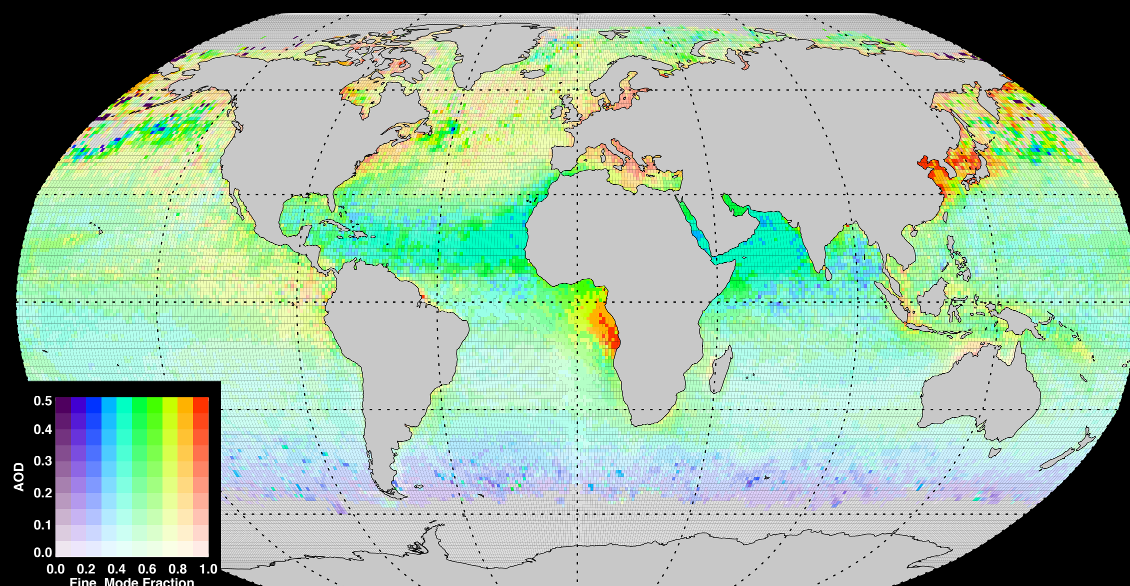


Mid-Visible
AOD
“Dark Target” + “Deep Blue”

MODIS
July 2010
Monthly Average



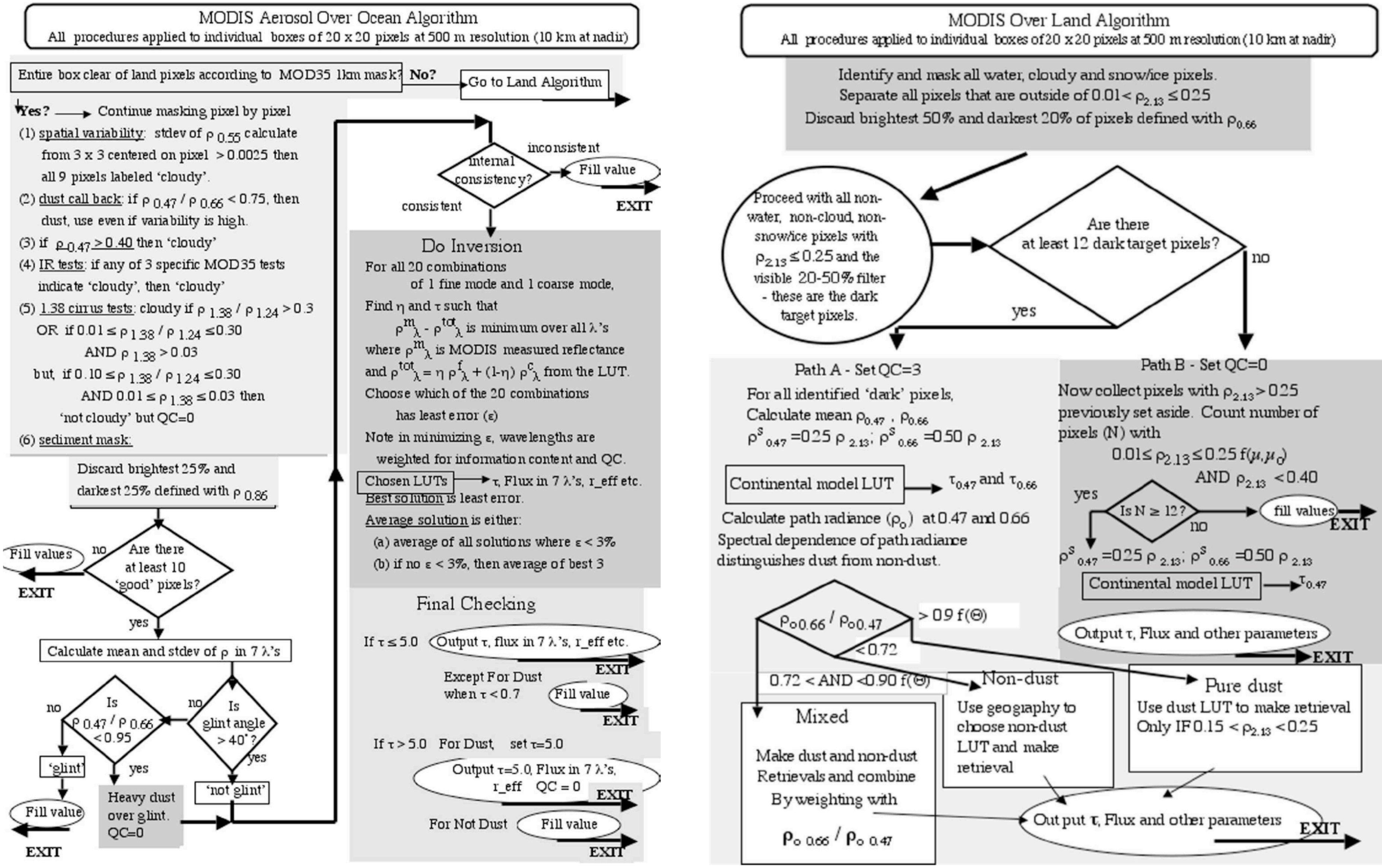
- Water & some Land
- Globe ~ Every 2 days
- ~ 10:30 AM & 1:30 PM



- Fine/Coarse Ratio Over Water + AOD
- Sensitivity to PM10

MODIS Team, NASA Goddard Space Flight Center

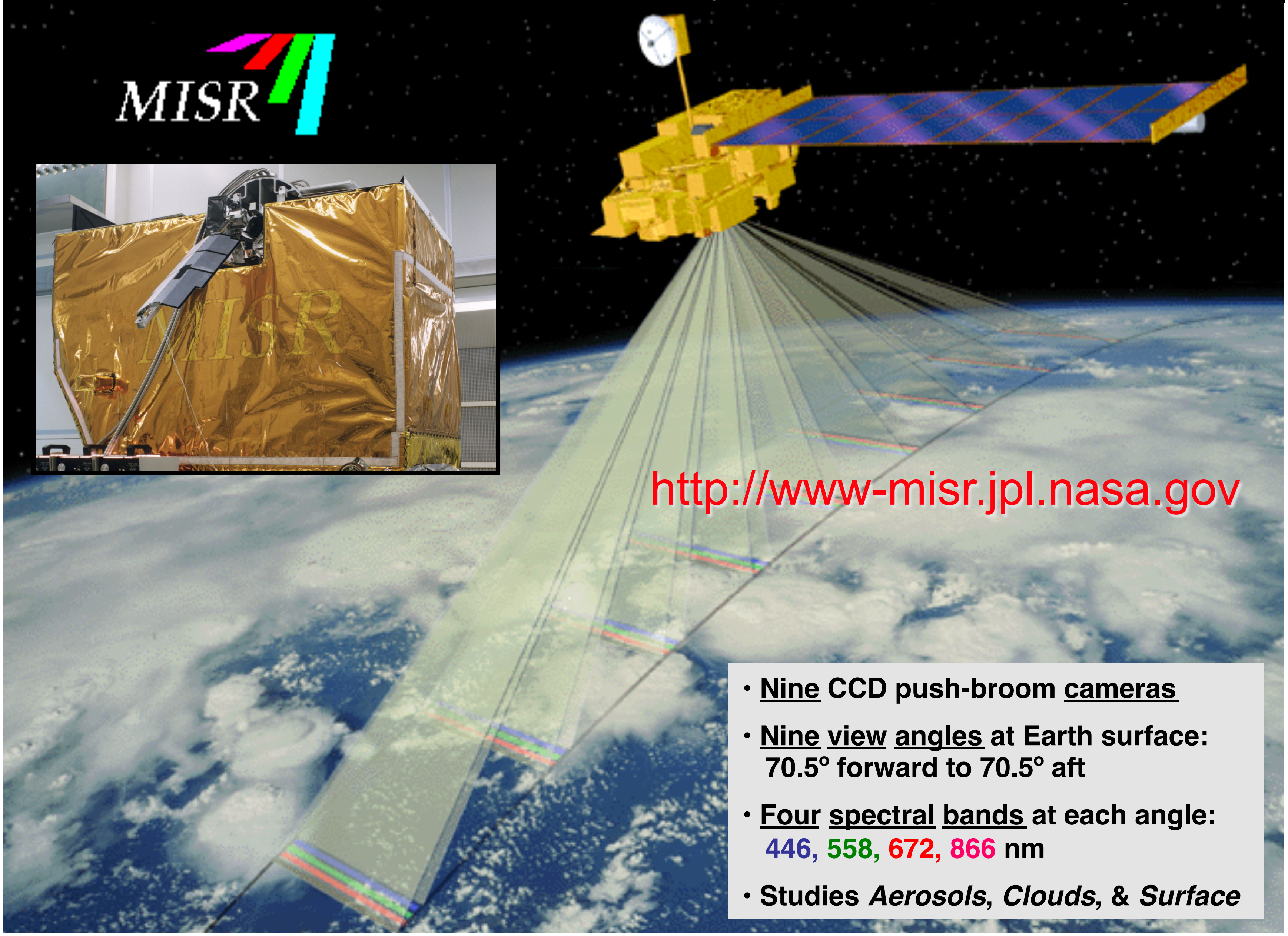
MODIS Aerosol Retrieval Algorithm Steps



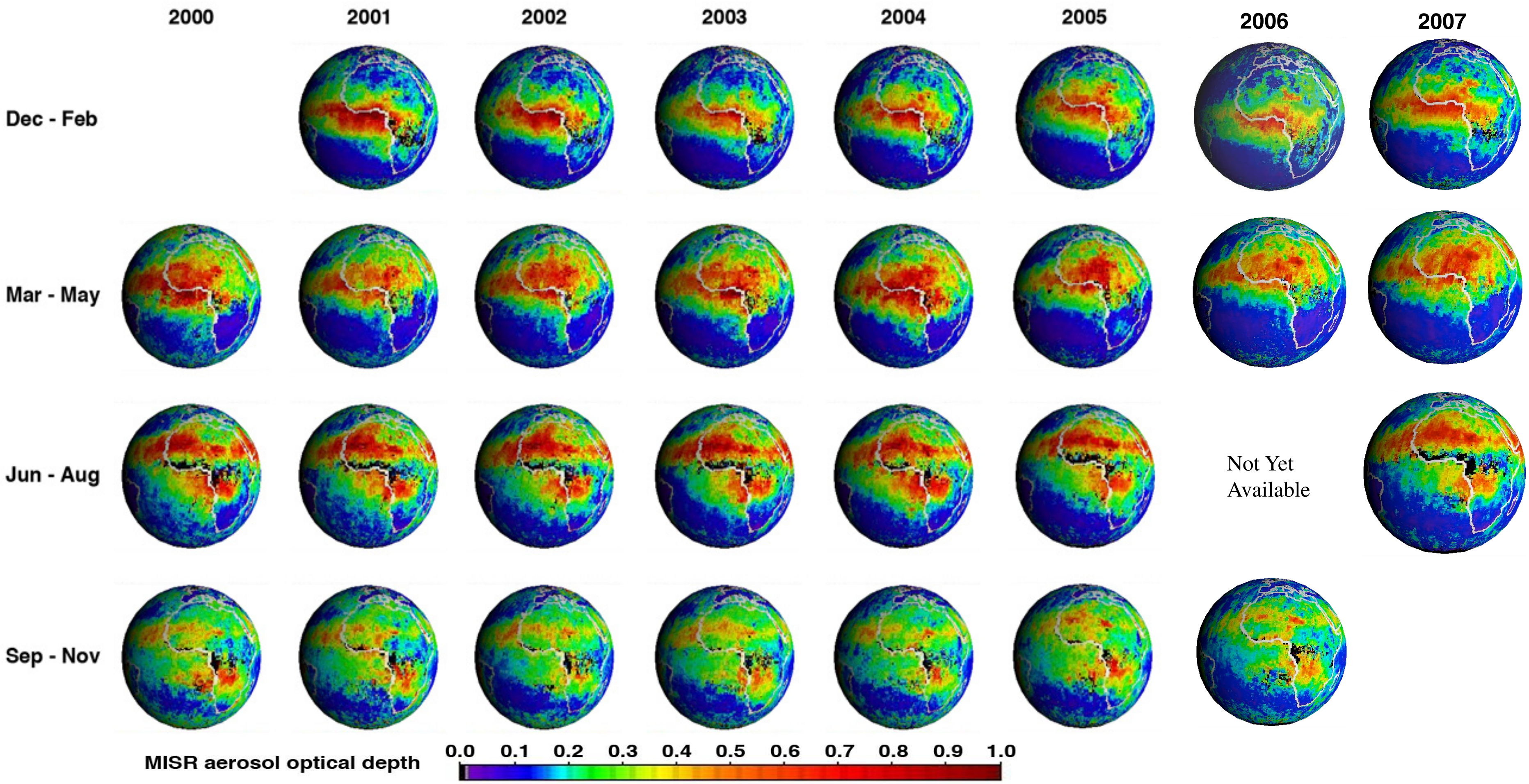
Ocean **Land**

Remer et al., JAS 2005

Multi-angle Imaging SpectroRadiometer



Eight Years of Seasonally Averaged Mid-visible Aerosol Optical Depth from MISR

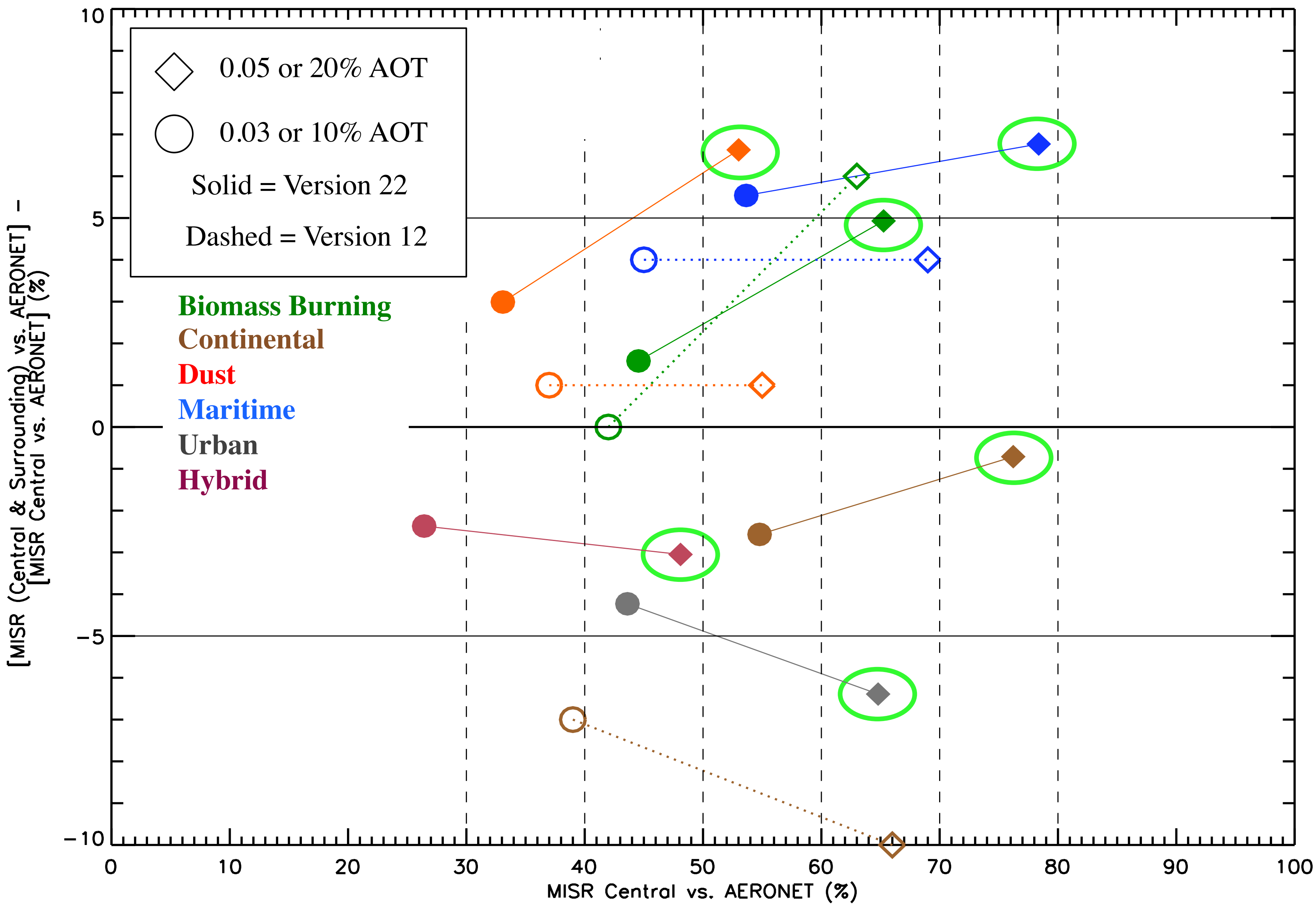


…includes bright desert dust source regions

MISR Team, JPL and GSFC

MISR-AERONET AOT Comparison for 3,995 Coincidences

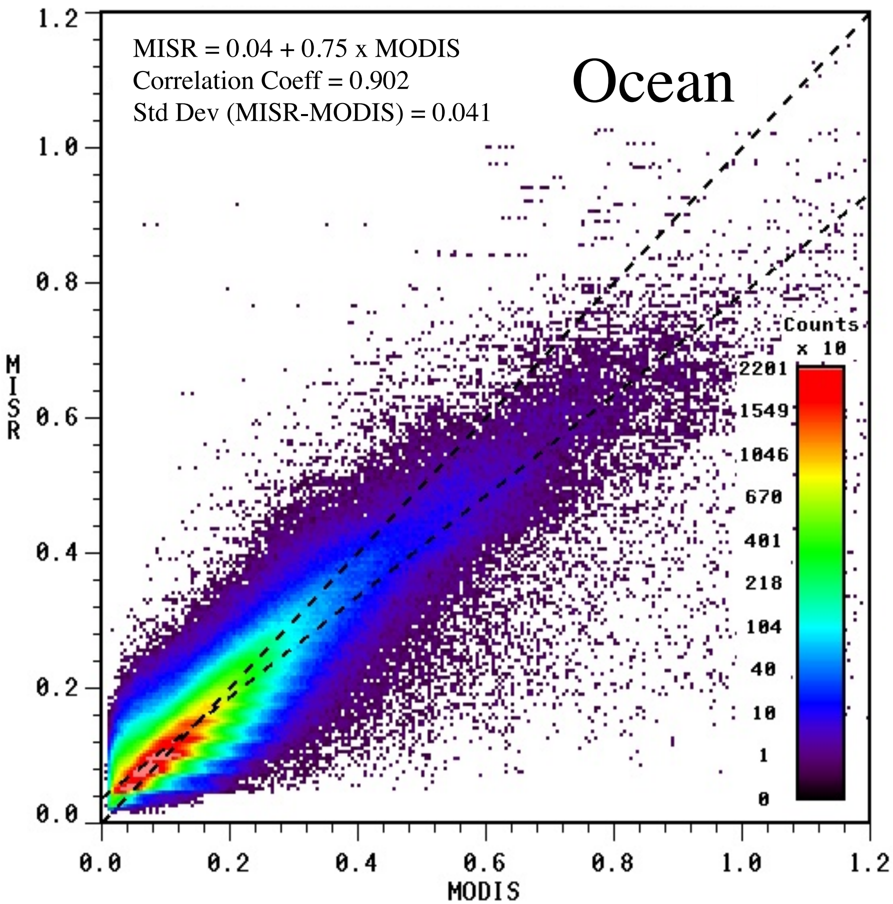
Stratified by expected aerosol air mass type

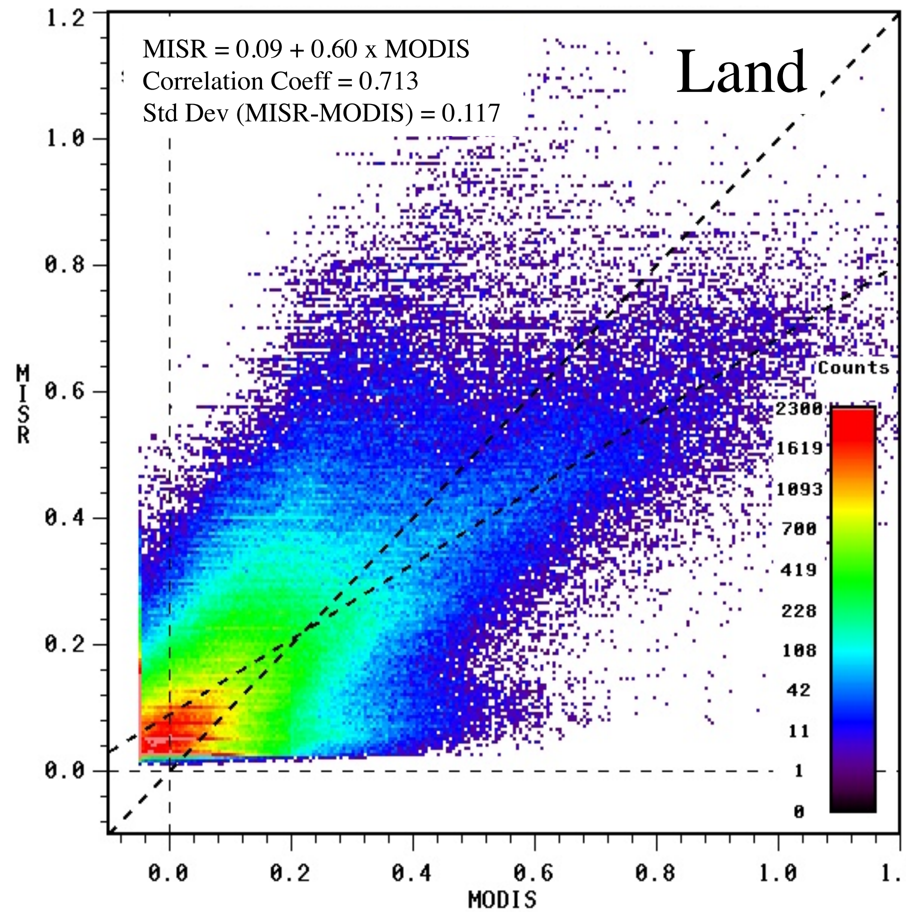


Kahn, Gaitley et al., JGR 2010

MISR-MODIS Aerosol Optical Depth Comparison

[MISR V22 vs. MODIS/Terra Collection 5; January 2006 Coincident Data]



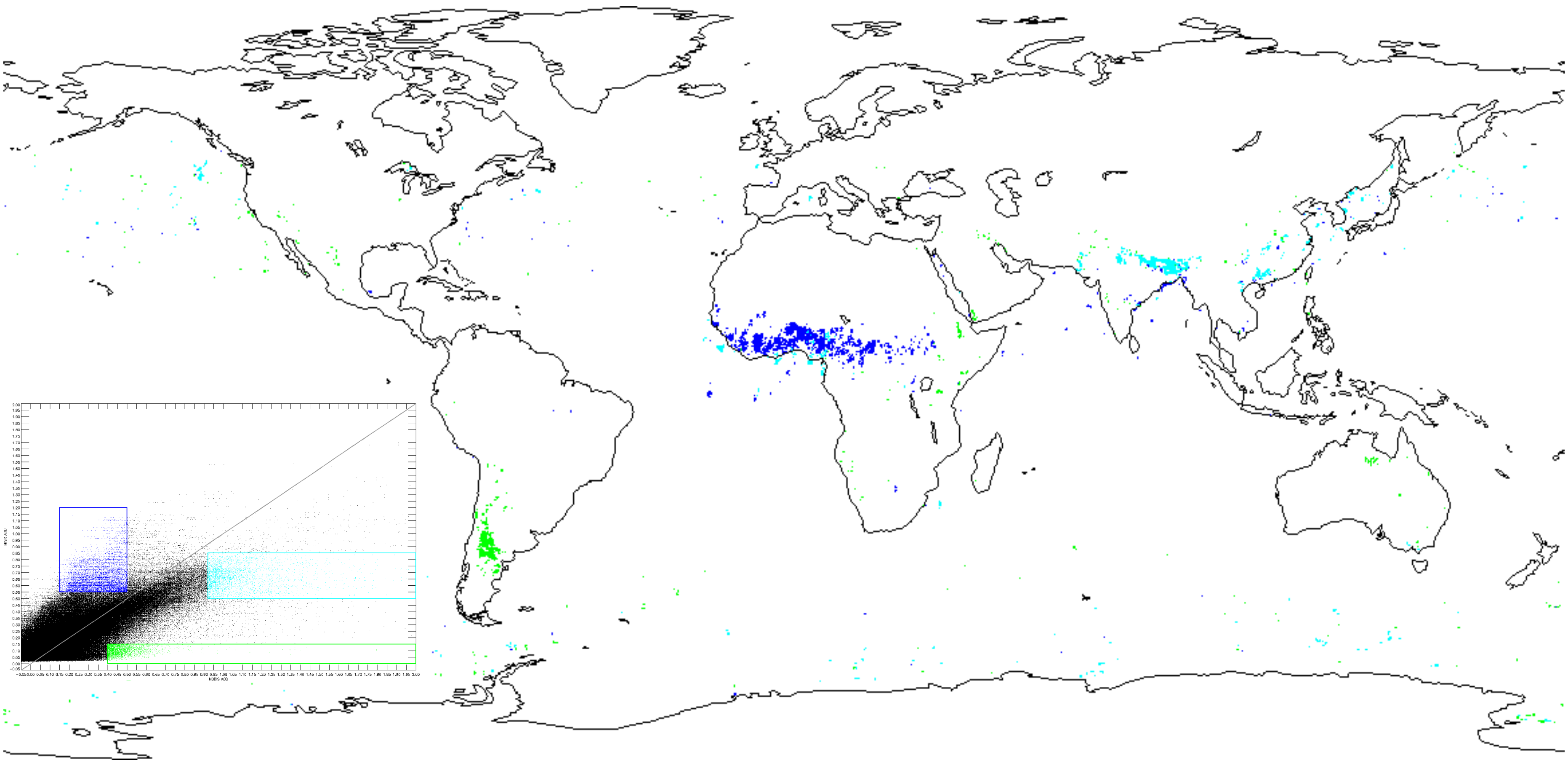


Over-ocean regression coefficient **0.90**
Regression line slope 0.75
MODIS QC ≥ 1

Over-land regression coefficient **0.71**
Regression line slope 0.60
MODIS QC = 3

Kahn, Nelson, Garay et al., TGRS 2009

MISR-MODIS Coincident AOT *Outlier Clusters*



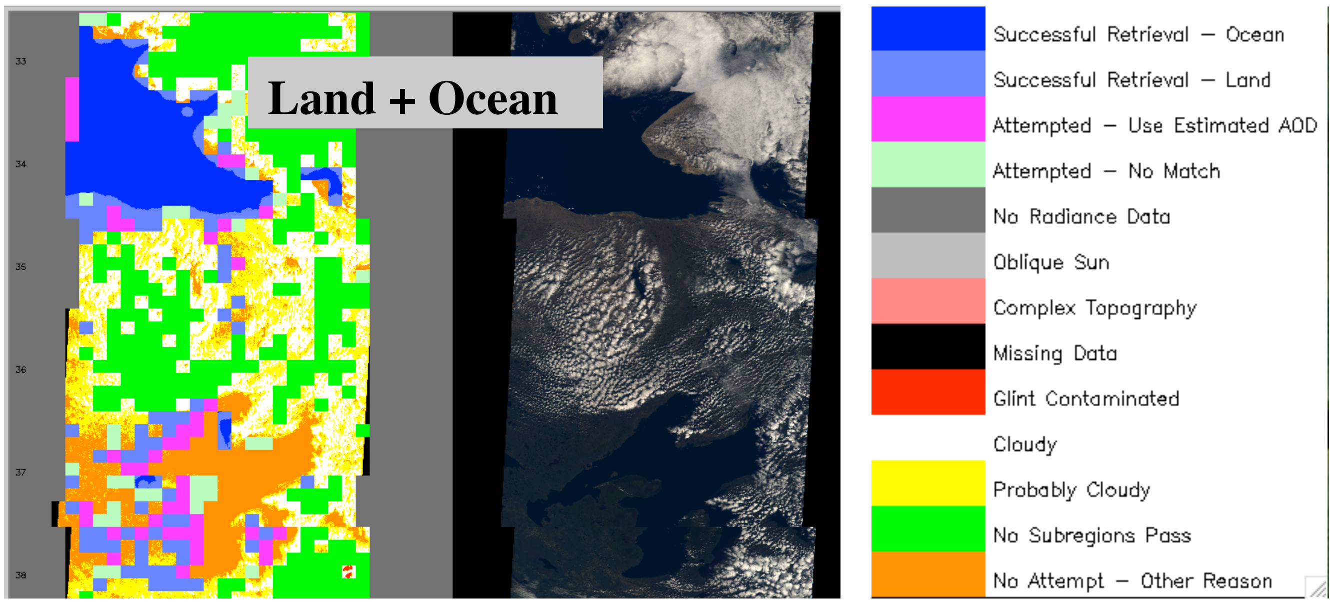
Dark Blue [MISR > MODIS] – N. Africa ***Mixed Dust & Smoke***
Cyan [MODIS > MISR, AOD large] – Indo-Gangetic Plain ***Dark Pollution Aerosol***
Green [MODIS >> MISR] – Patagonia and N. Australia ***MODIS Unscreened Bright Surface***

Kahn et al., TGARS 2009

MISR Retrieval Status Distribution

Overall, about **15%** of Earth's surface produces successful MISR automatic aerosol retrievals

Dark blue = Ocean retrieval
Light blue = Land retrieval

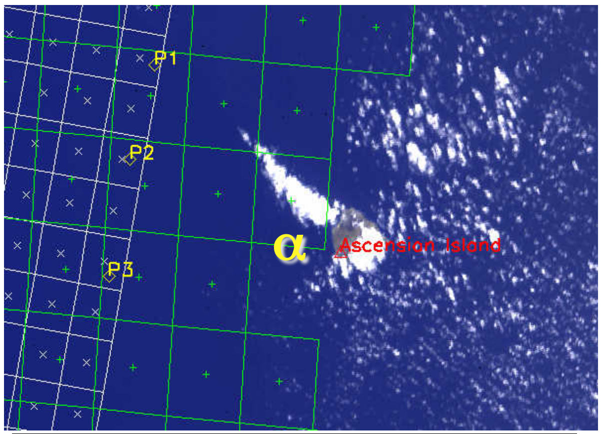


Kahn, Nelson, Garay et al., TGRS, 2009

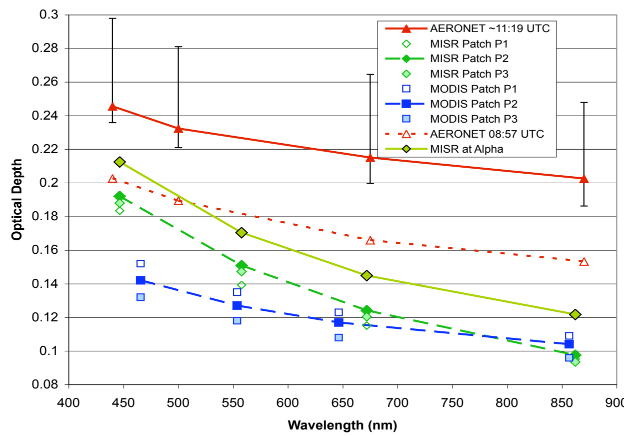
From experience with MISR & MODIS:

For global, ~ 1° × 1° AOD, in general, MISR data need to be aggregated to ***~ 3-month sampling*** *to converge with MODIS*

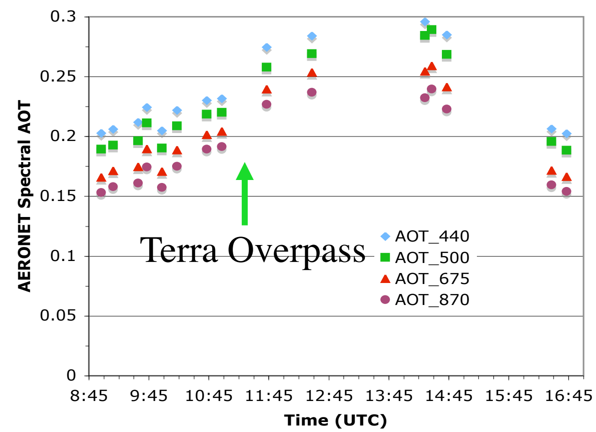
MISR-MODIS-AERONET *Sampling* Differences
[Ascension Island 18 February 2005]



Sampling: MISR; MODIS; AERONET



AOT Snapshot: ARNET> MISR >MODIS



AERONET Time Series - Changing AOT

Kahn et al., JGR 2007

Clean, maritime aerosol air mass, but AOT changes 60% across RH boundary

Using any one of these to represent the entire region AOT --> large errors
Taken together, they give a better picture…

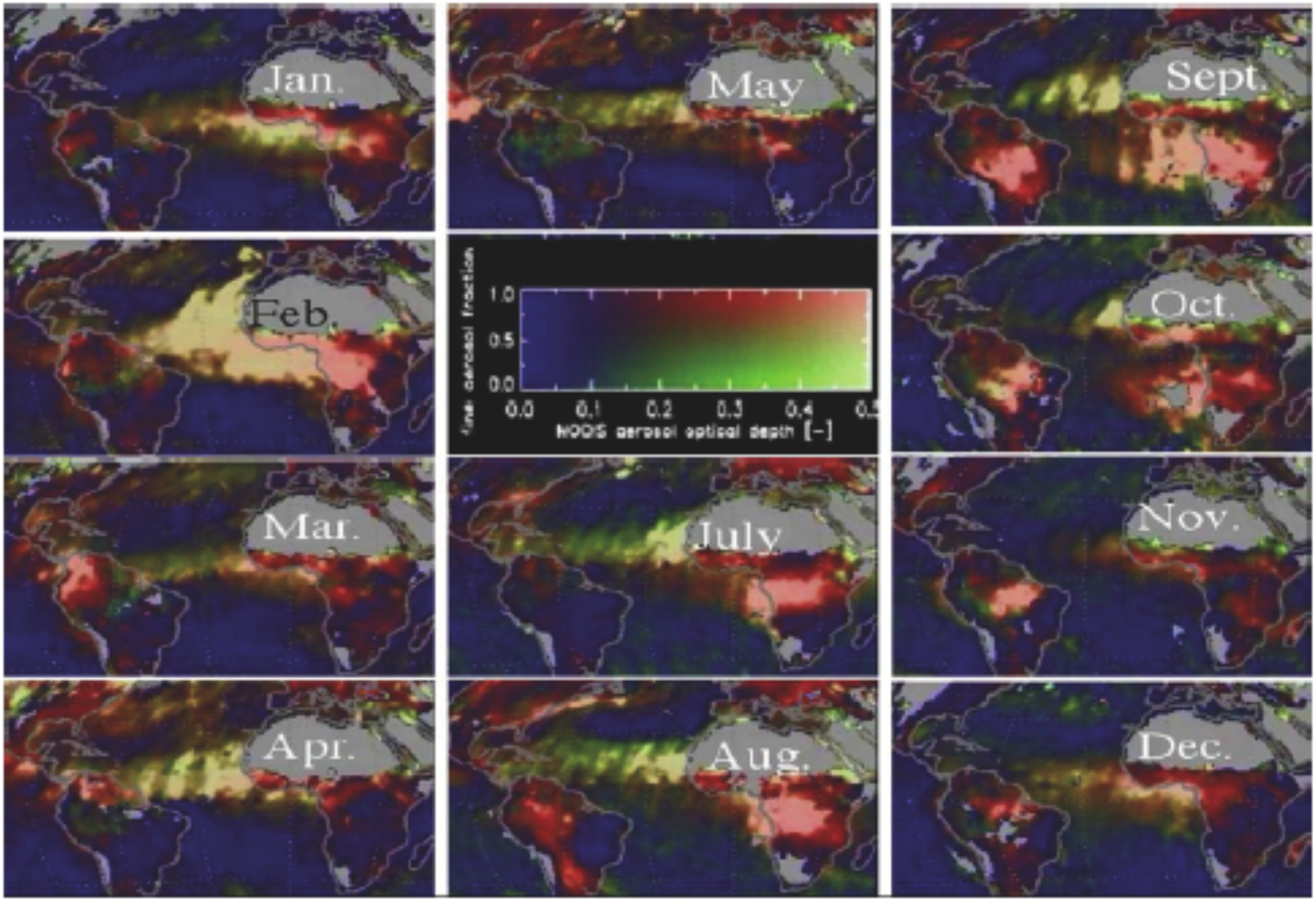
***Sampling Effects* is a continuing story…**

Aerosol Retrievals –

Aerosol Type

One MODIS Aerosol Type Classification:

Low AOT (blue), **High AOT+Coarse** (green), **High AOT+Fine** (red)

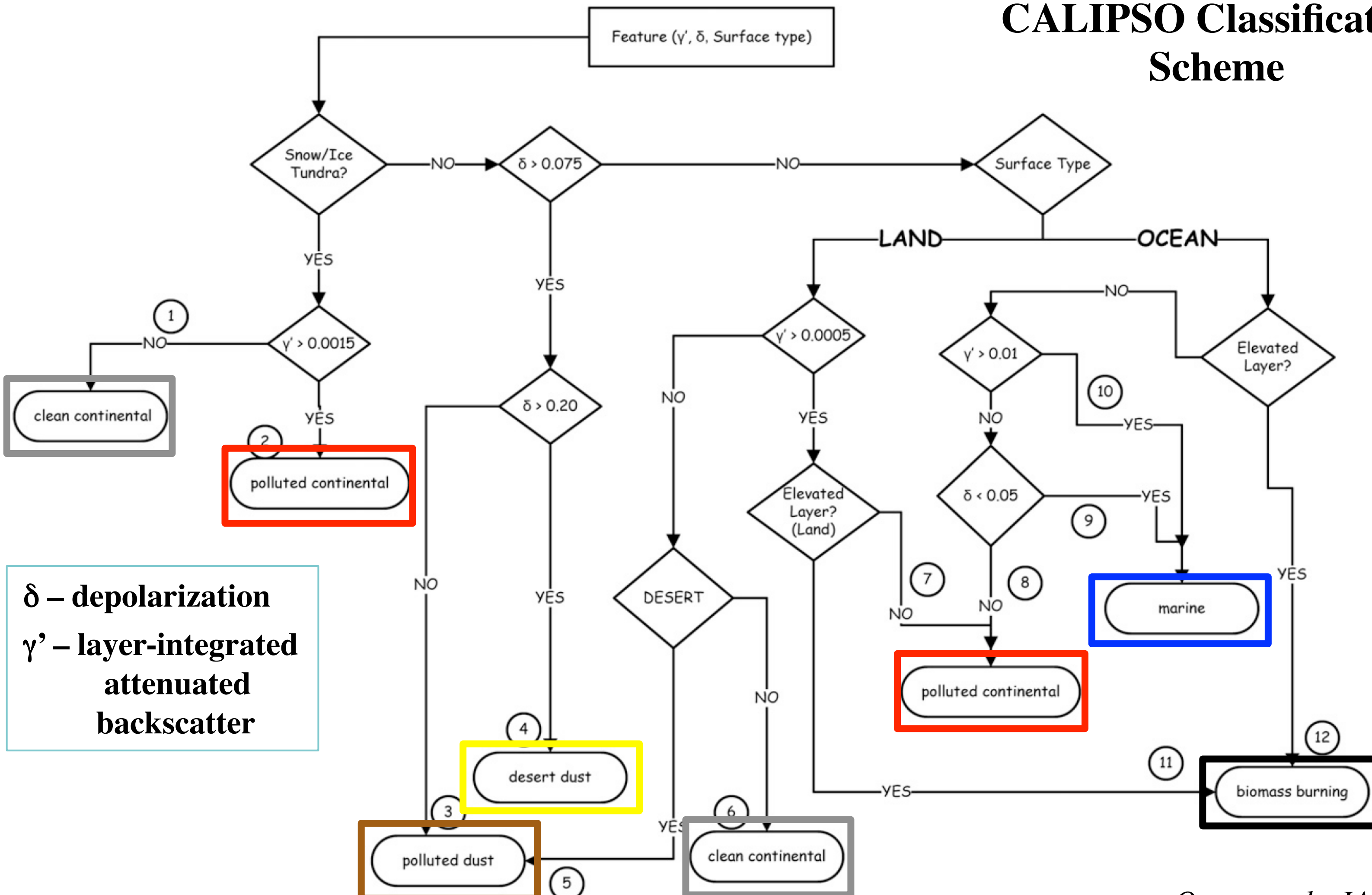


From: *Kaufman et al*., JGR, 2005

Progress Toward a Global Aerosol Type Climatology

Ralph Kahn
NASA/Goddard Space Flight Center

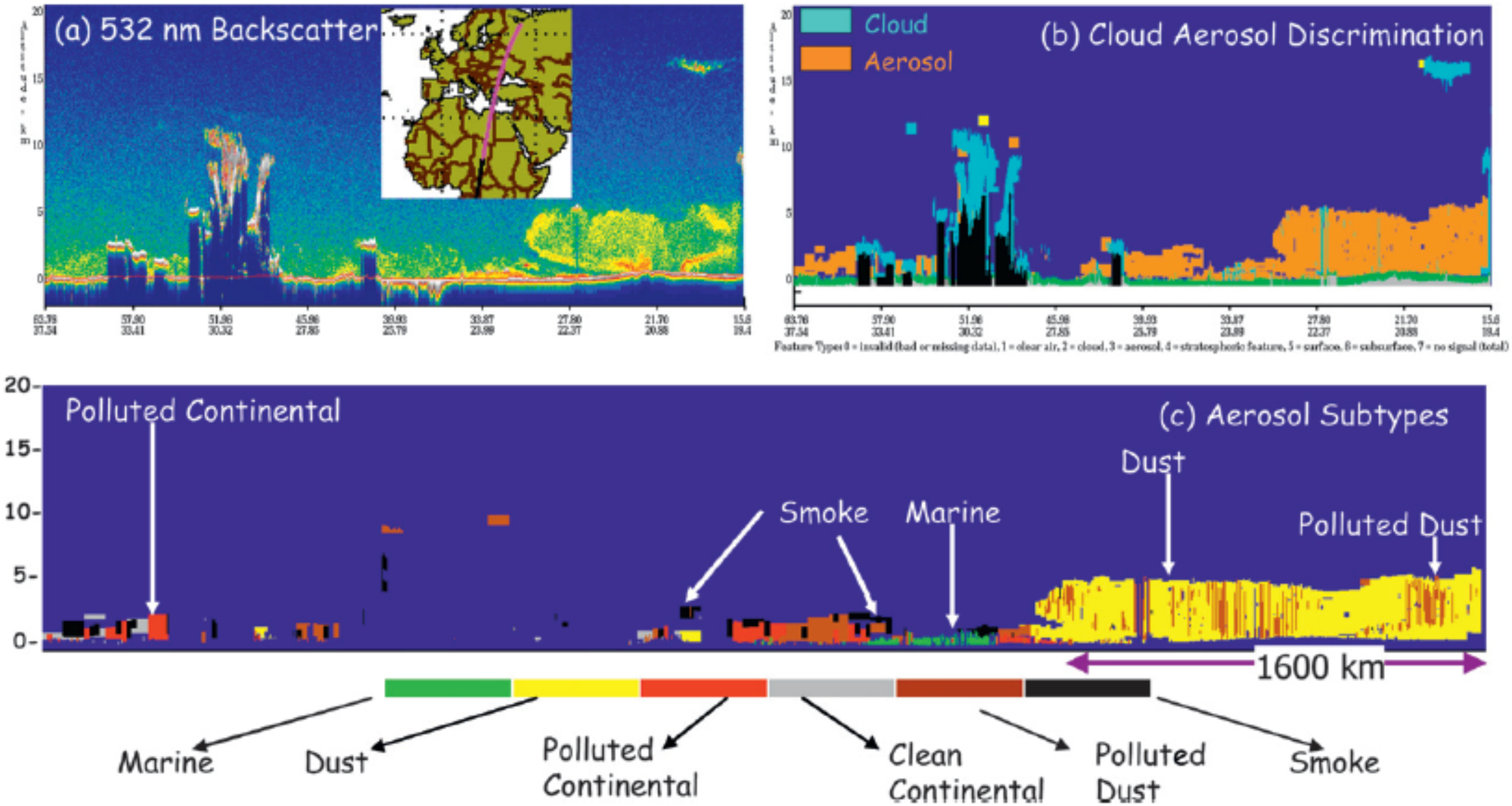
CALIPSO Classification Scheme



δ – depolarization
γ' – layer-integrated attenuated backscatter

Omar et al., JAOT 2009

CALIPSO 6-Grouping Aerosol Type Classification

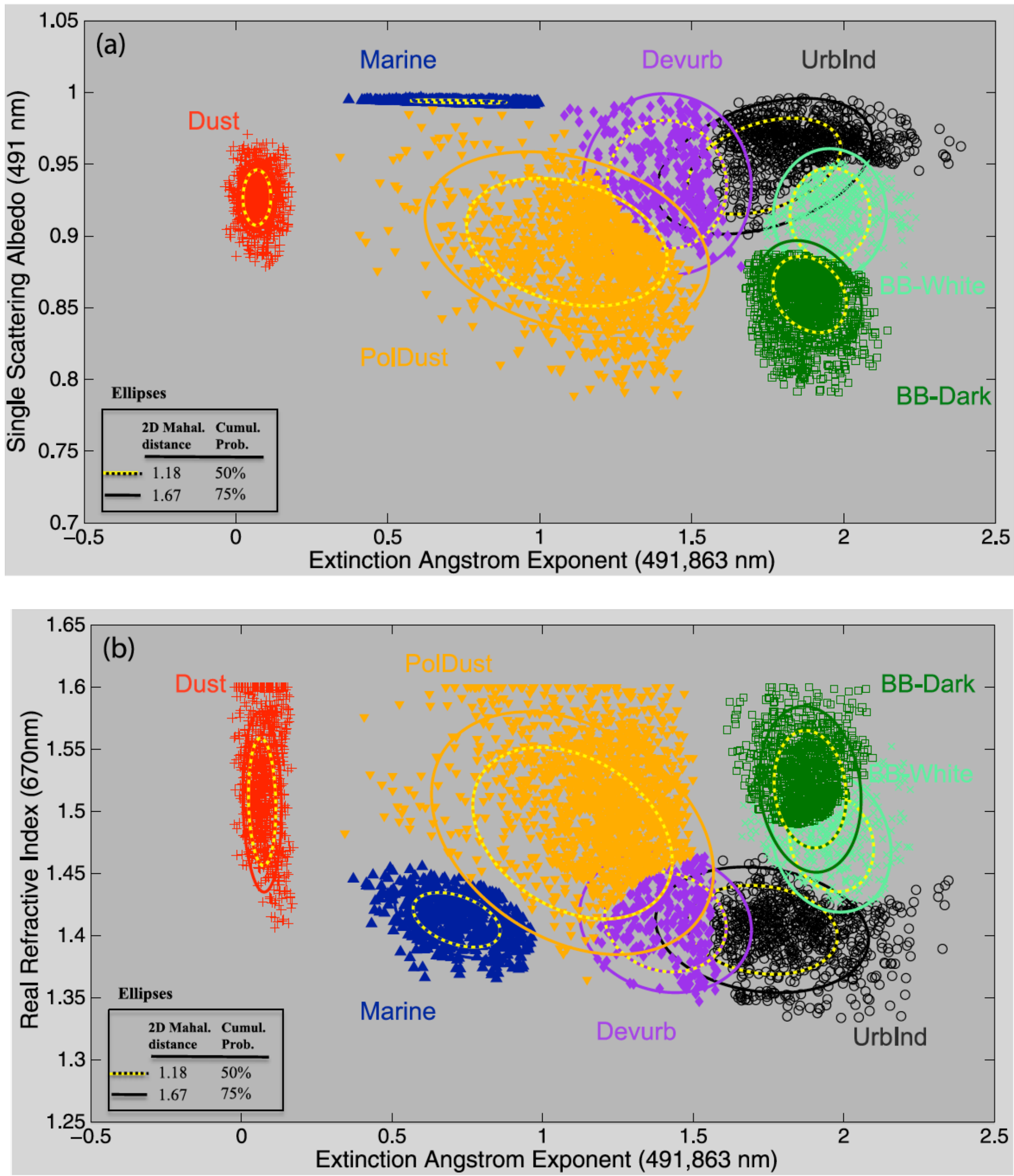


Omar et al., JAOT 2009

AERONET Aerosol Type 7-Grouping Classification

Four-parameter AERONET-derived classification:

- $EAE_{491,863}$
- SSA_{491}
- RRI_{670}
- $dSSA_{863-491}$



7 Groupings SSA_{491} vs. Extinction ANG

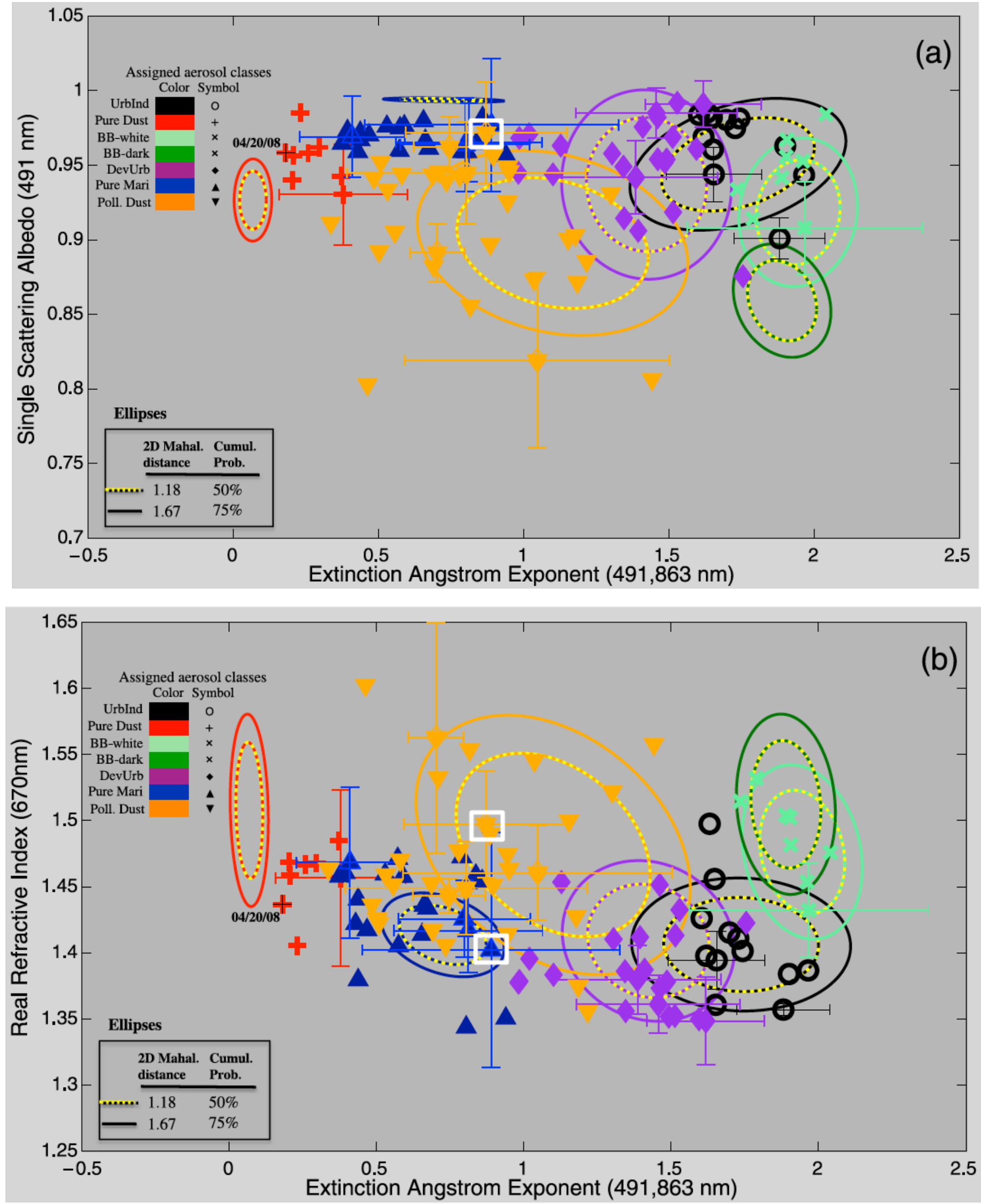
7 Groupings Real RI_{670} vs. Extinction ANG

Russell et al. JGR 2014

PARASOL data at Forth Crete projected onto the AERONET Aerosol Type Classification

Four-parameter AERONET-derived classification:

- $EAE_{491,863}$
- SSA_{491}
- RRI_{670}
- $dSSA_{863-491}$

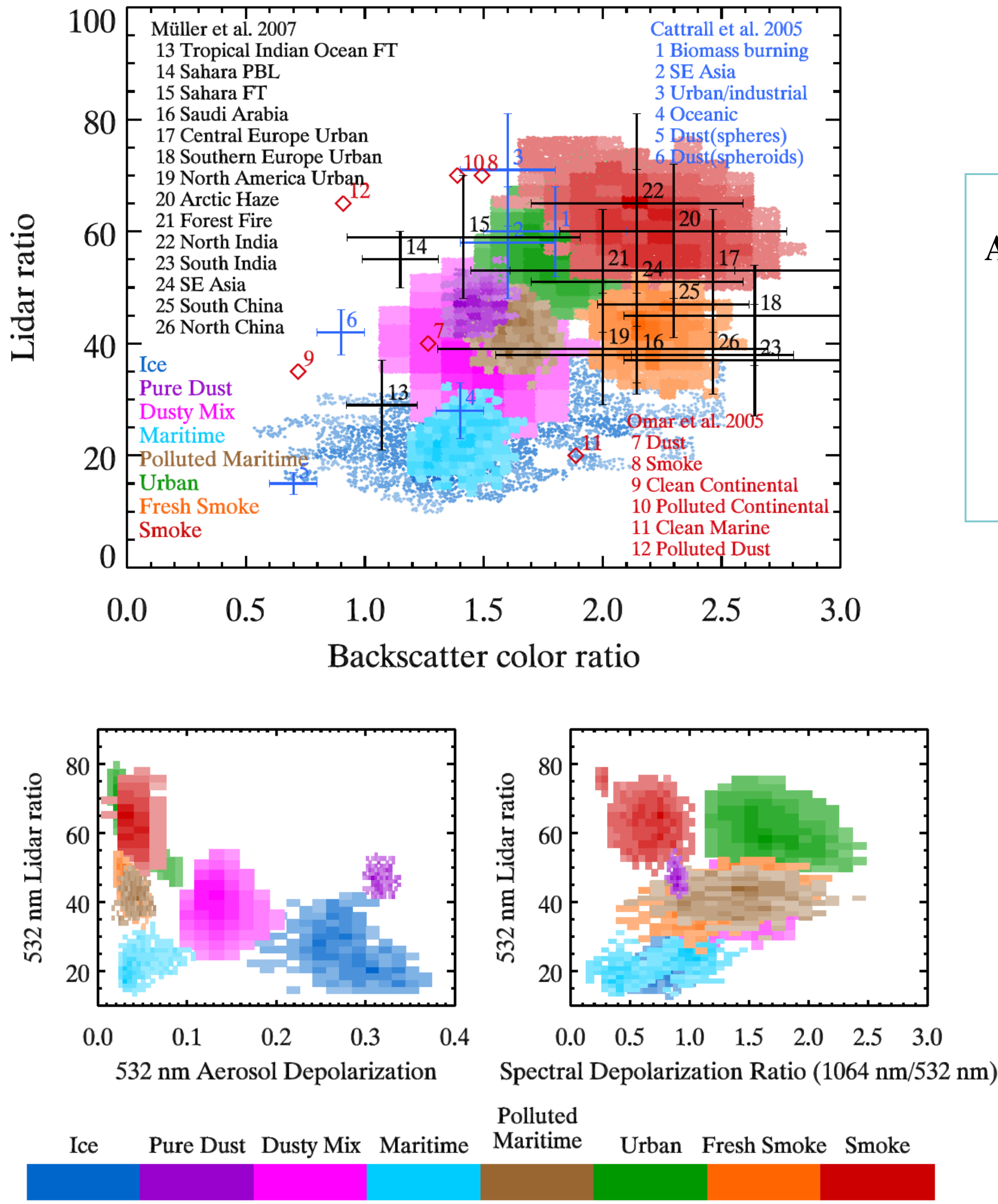


7 Groupings SSA_{491} vs. Extinction ANG

7 Groupings Real RI_{670} vs. Extinction ANG

Russell et al. JGR 2014

HSRL Aerosol Type 8-Grouping Classification



Four-parameter AERONET-derived classification:

- α_{532}/β_{532}
- β_{1064}/β_{532}
- δ_{532}
- $\beta_{1064}/\delta_{532}$

Burton et al. JGR 2012

Aerosol_cci
(European Consortium)

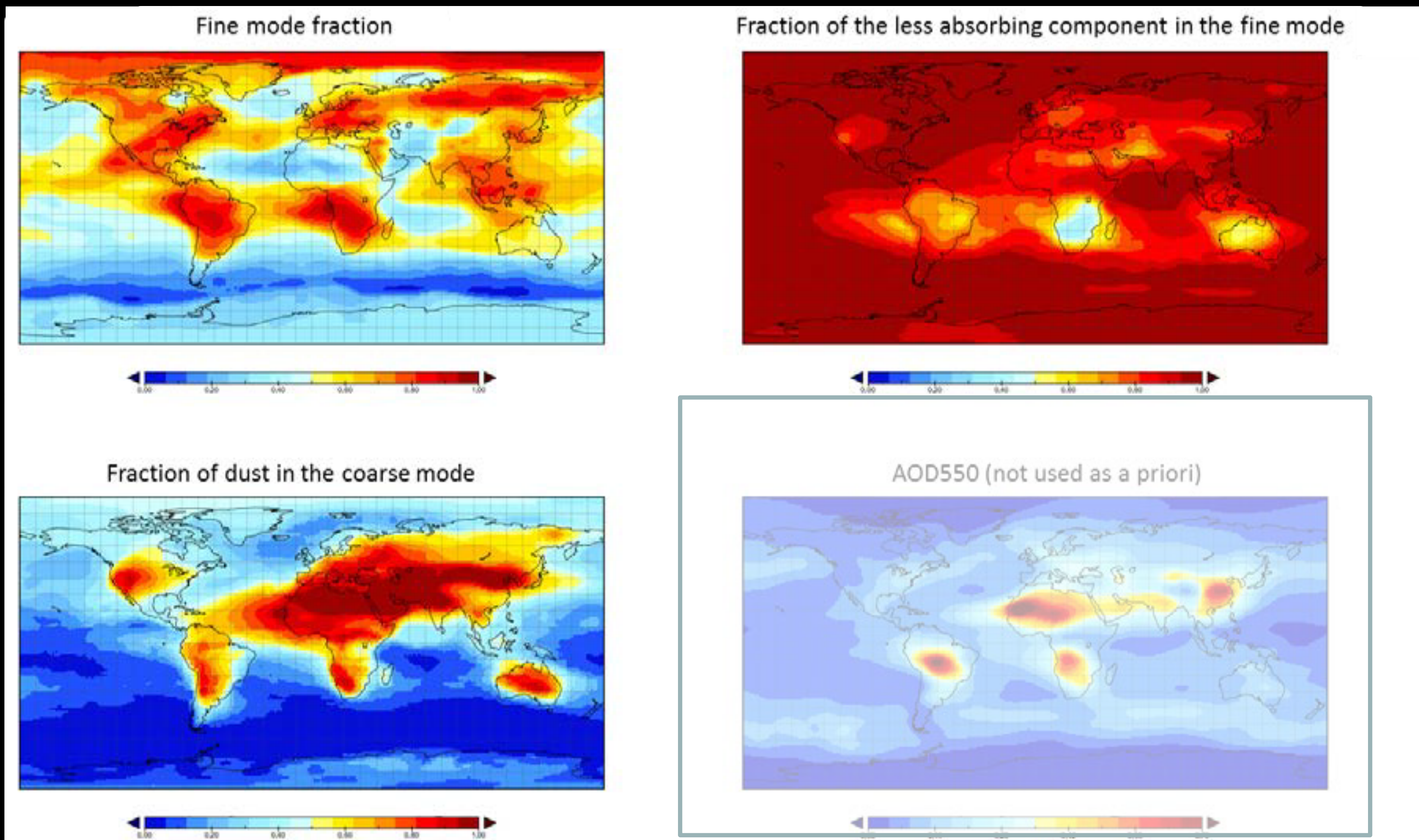
- 4 basic components

  (Dust, Sea Salt, Fine-mode Weakly & Strongly Abs.
- Reflects theoretical information content
- External mixtures with 3 mixing fractions
- Evaluation ongoing of information content

- Output (easier to validate / compare)
  - Fine mode AOD (fine mode / total mixing fraction)
  - Dust AOD (dust / total coarse mode mixing fraction)
  - [AAOD (absorption fraction in fine mode)]

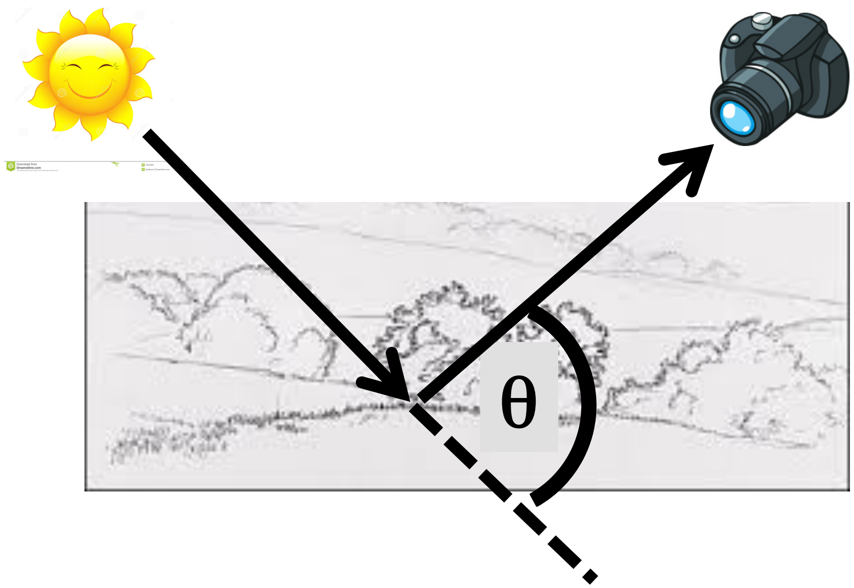
From: Thomas Popp

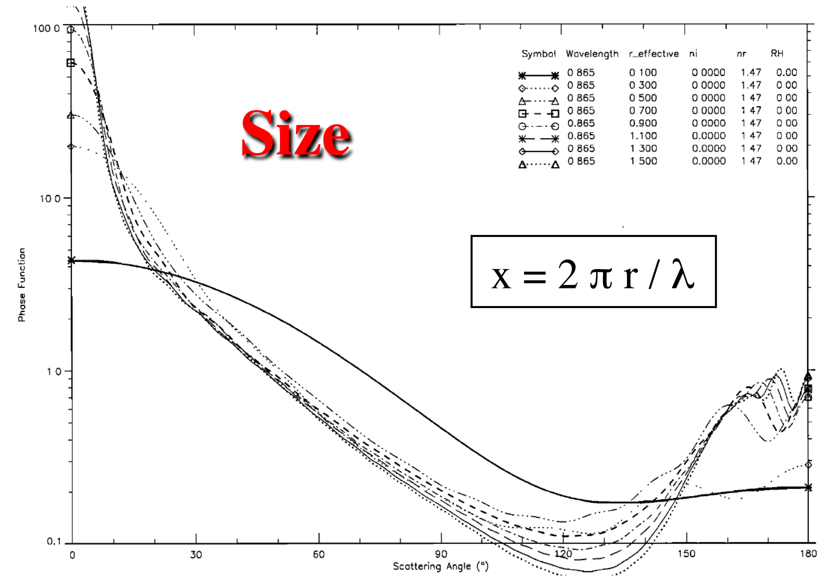
cci AOD mixing (fractions)
from AEROCOM Models

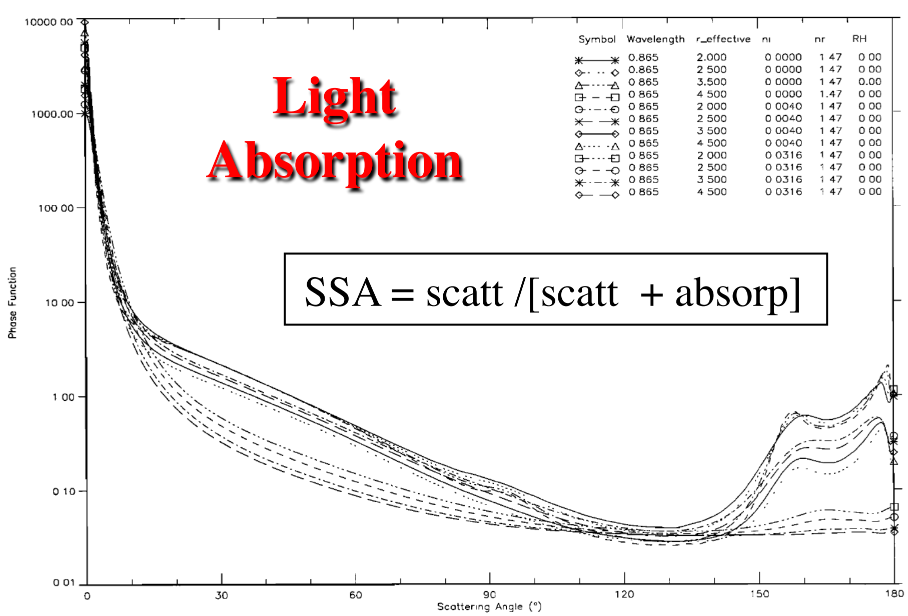


From: Thomas Popp

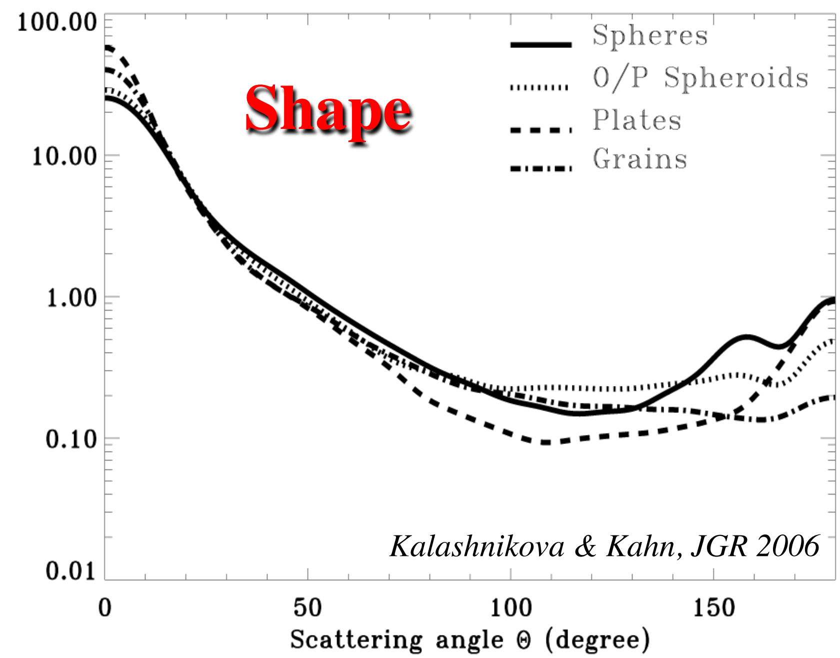
Single-scattering Phase Functions for **Different Particle Properties**







Kahn et al., JGR 1998



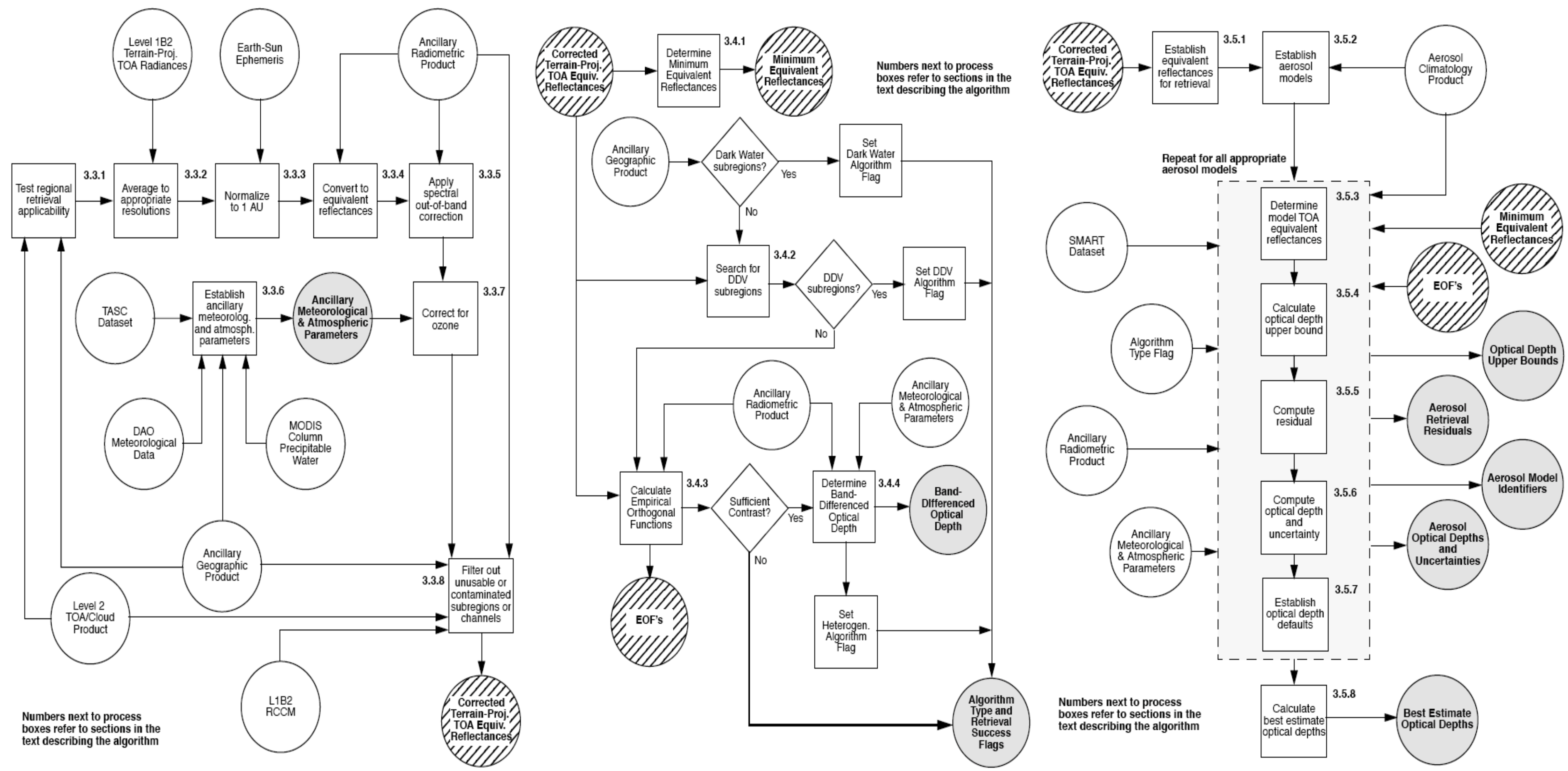
Los Alamos Fire, New Mexico May 9, 2000

MISR 60˚ Forward

MISR Nadir

MISR 60˚ Aft

Broad Outline of MISR Aerosol/Surface Retrieval Algorithm Steps



Stage 1
- Cloud, terrain masks
- Band & Gas corrections
- Convert to Eq. Reflectance

Stage 2
- Select water or land algorithm
- Aggregate Eq. Reflectances
- Calculate EOFs if land

Stage 3
- Compare measurements with pre-calculated options
- Calculate uncertainties

Key Algorithm Inputs & Assumptions

Stage 1
- Calibration (band corrections, etc.)
- Surface Type Information (terrain type, snow mask, wind, etc.)
- Atmospheric gas concentrations (O_3, H_2O_v, etc.)
- Ephemeris & solar input
- Cloud masking

Stage 2
- Aggregation (How to select & process the Stage 1 reflectances)
- Retrieval approach (What to assume or derive about aerosols & surface)**

Stage 3
- Aerosol components & mixtures
- Aerosol vertical distribution
- Radiative transfer code(s)
- Look-up table resolution
- Acceptance criteria
- Uncertainty metrics

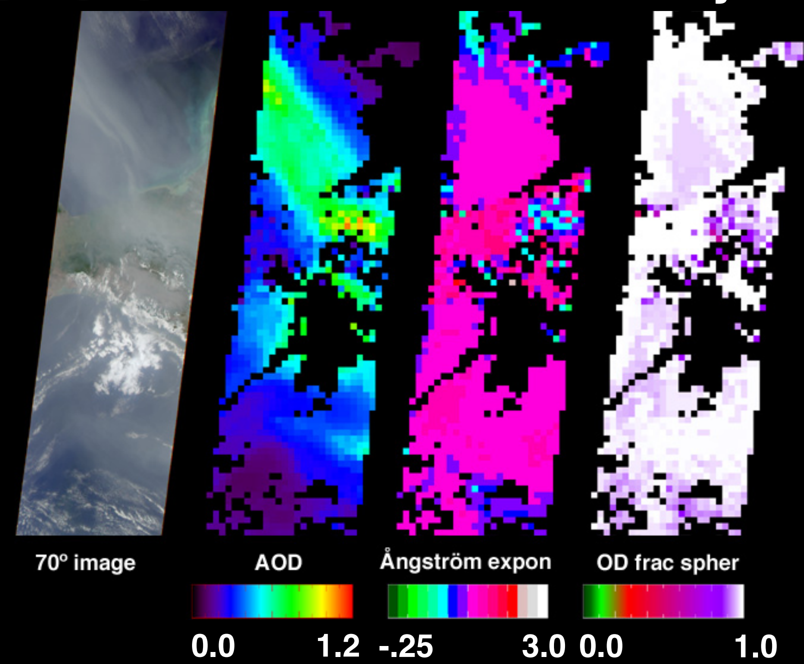
** Retrieved Quantities ←→ Information Content of the data

Pre-launch Sensitivity Studies, Post-launch Validation

Kahn et al., JGR 2007

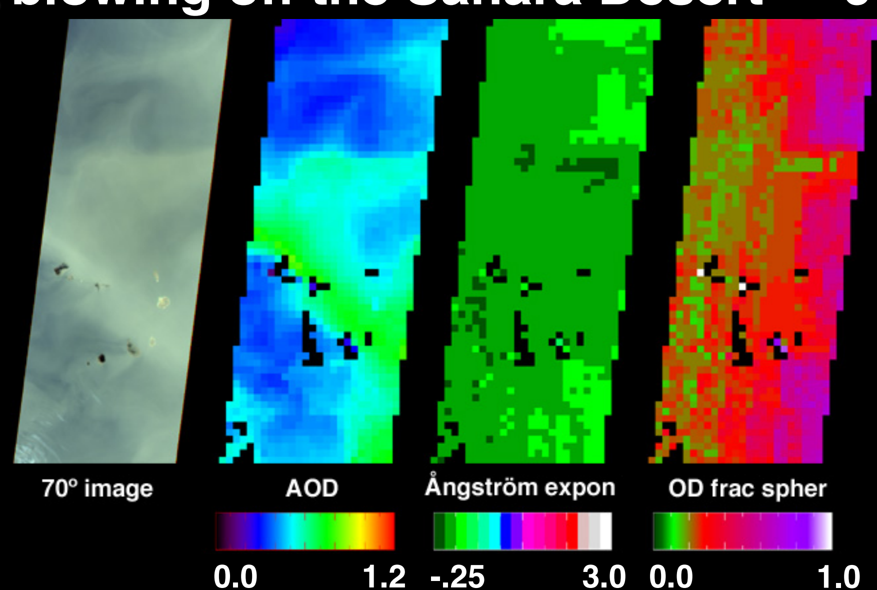
Smoke from Mexico -- 02 May 2002

Aerosol:
Amount
Size
Shape



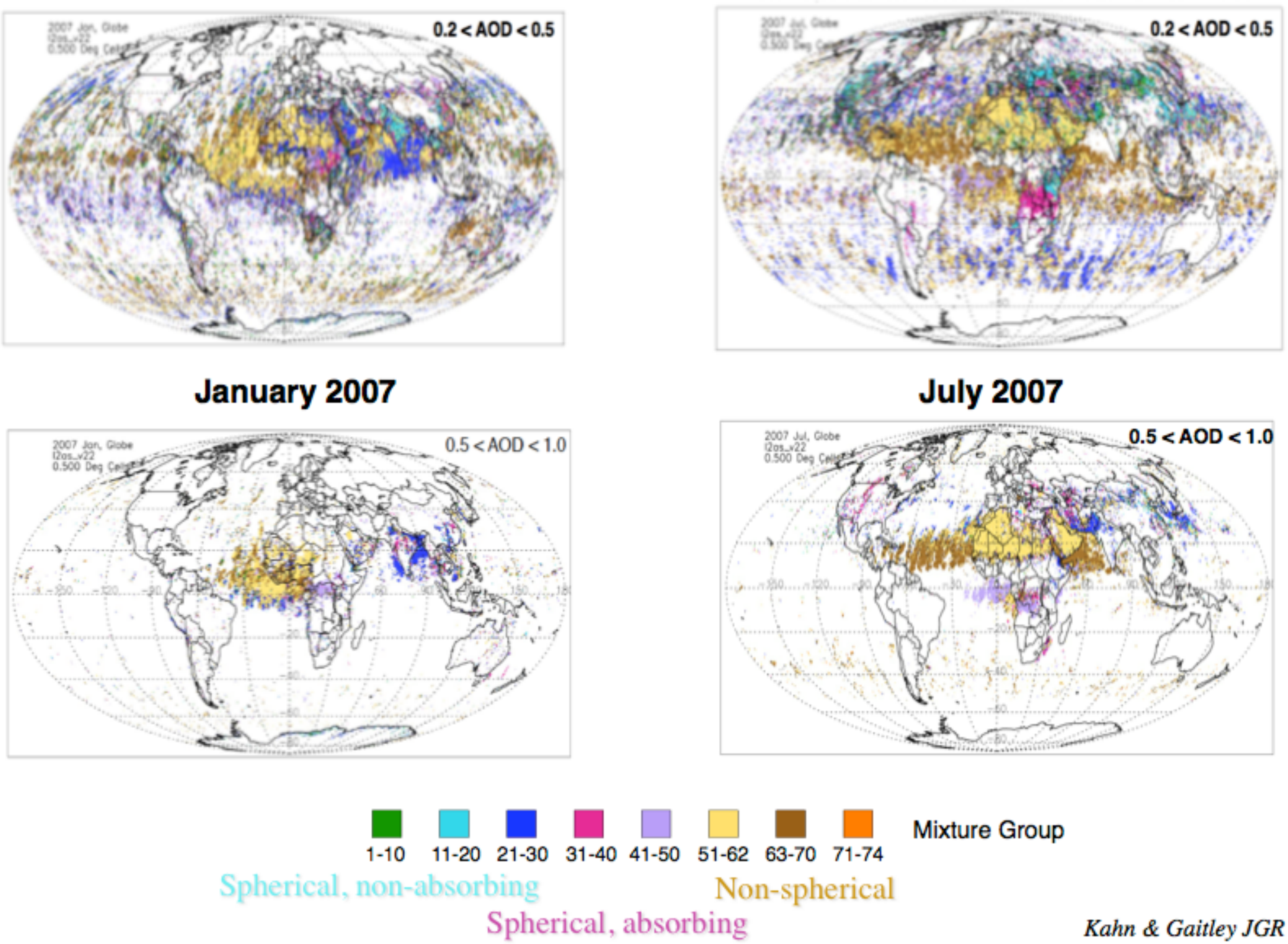
Medium
Spherical
Smoke
Particles

Dust blowing off the Sahara Desert -- 6 February 2004



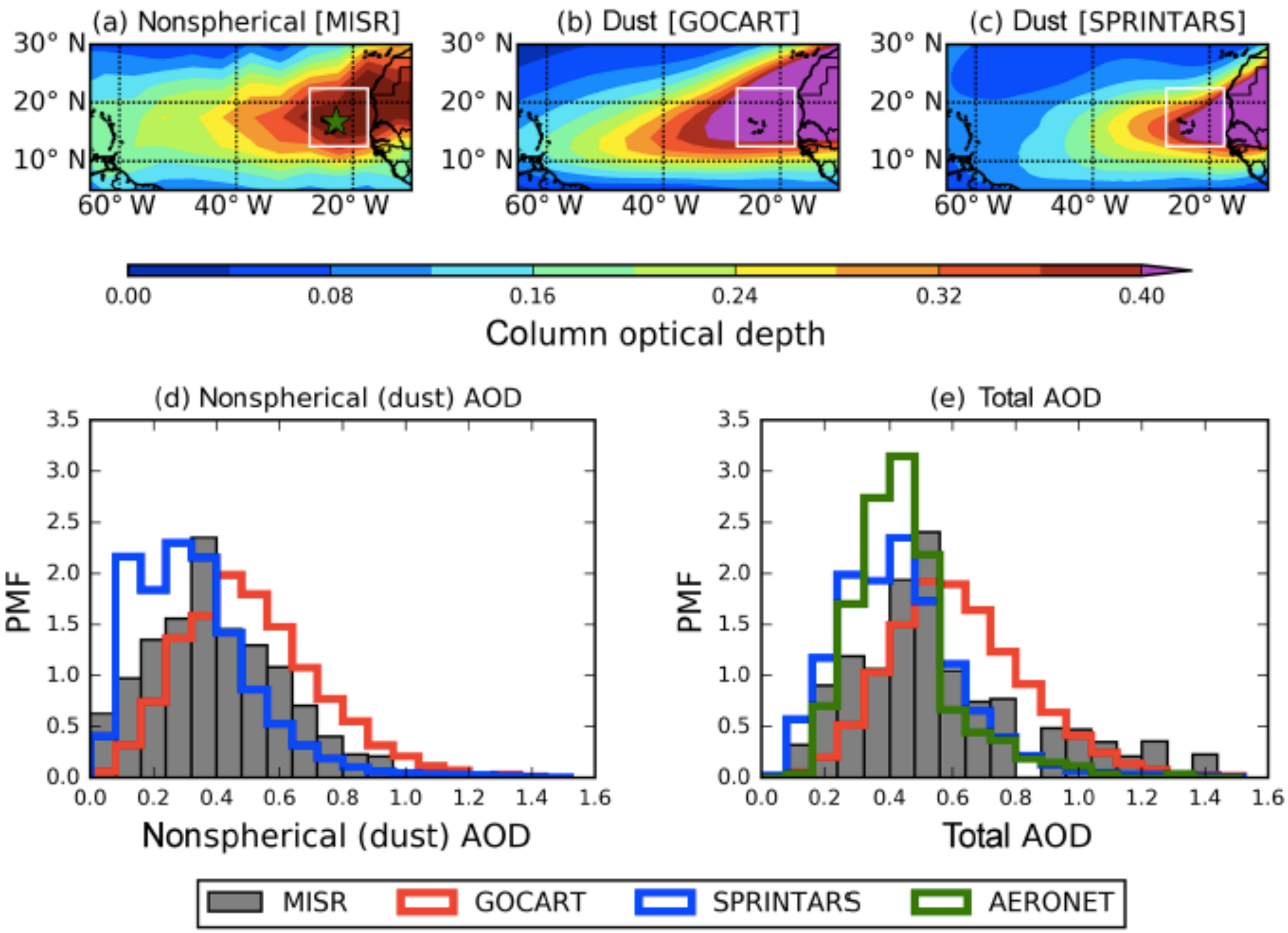
Large
Non-Spherical
Dust
Particles

MISR Aerosol Type Discrimination



Kahn & Gaitley JGR 2015

MISR Climatology Dust AOD



Huikyo Lee et al. ACP 2016

Aerosol Type Summary

- Remote-sensing can provide optical constraints interpreted as particle ***Size, Shape, and Indices of Refraction***

- A ***further*** interpretative step, entailing additional assumptions, reports particle ***Chemical Composition***

- Remote-sensing ***sensitivity to particle properties is much more dependent than AOD on retrieval conditions***

- ***Validation Data*** for aerosol type are very limited

  -- ***Model simulations*** and ***In Situ measurements*** can help

GRASP: Generalized Retrieval of Aerosol and Surface Properties

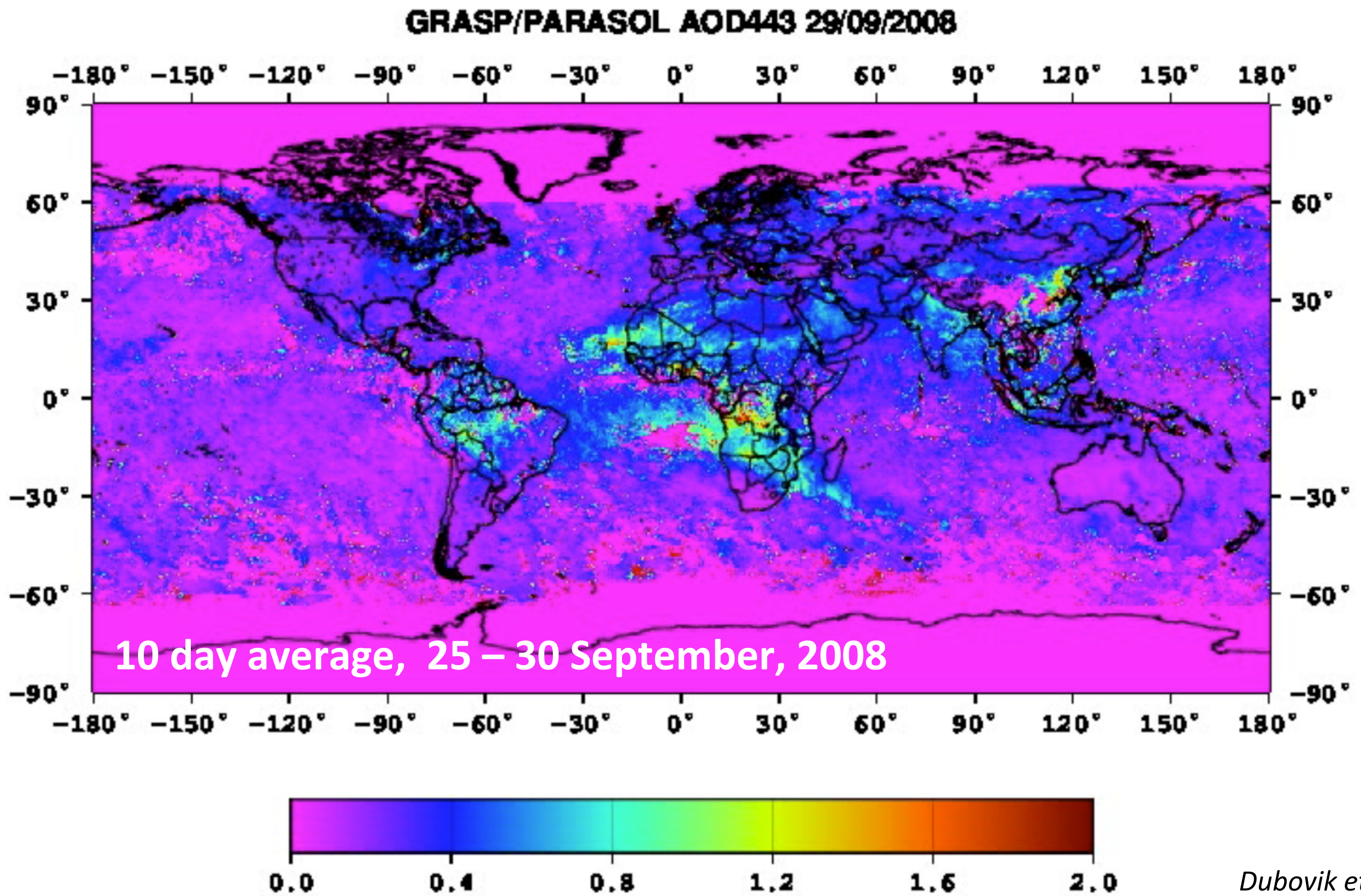
Open Source

No Location-Specific Assumptions on aerosol and surface

All calculation on the fly

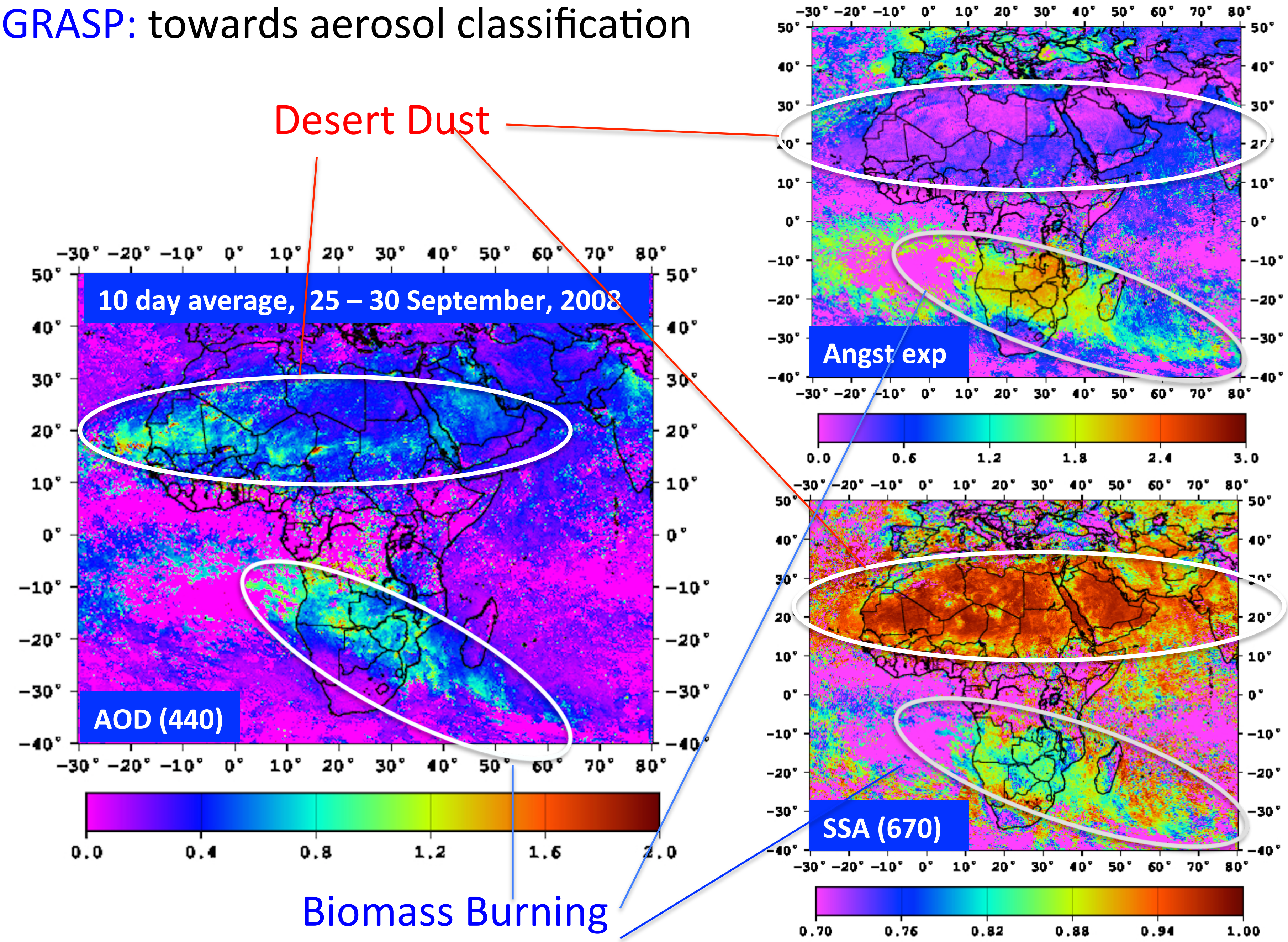
Retrieved parameters: Surface reflectance, aerosol: AOD, SSA, aerosol height, size information, refractive index, aerosol type, etc.

Expected practical advantages: accurate even over bright surfaces, even for high AOD, and for extended set of parameters



Dubovik et al. 2011, 2014

GRASP: towards aerosol classification



Dubovik et al. 2011, 2014

Aerosol Type Validation Approach

- No ***"Ground Truth"*** except from Field Campaigns (***Golden Days***)

  -- Unlike ***Spectral AOD*** (and ***ANG***) from AERONET
  Particle Properties derived from AERONET entail ***many more assumptions***

  -- ***Far fewer*** Satellite-AERONET Sky-scan that Direct-sun Coincidences

- ***Self-consistency*** Tests

  -- ***Qualitative***, but useful

  -- ***Regional*** and ***Temporal Behavior*** (stratified) vs. ***Expectation***

- ***Comparisons*** with AERONET proxies

  -- Compare ***Seasonal***, ***Inter-annual*** patterns ***Statistically***

  -- ***Fine-mode Fraction*** (FMF)

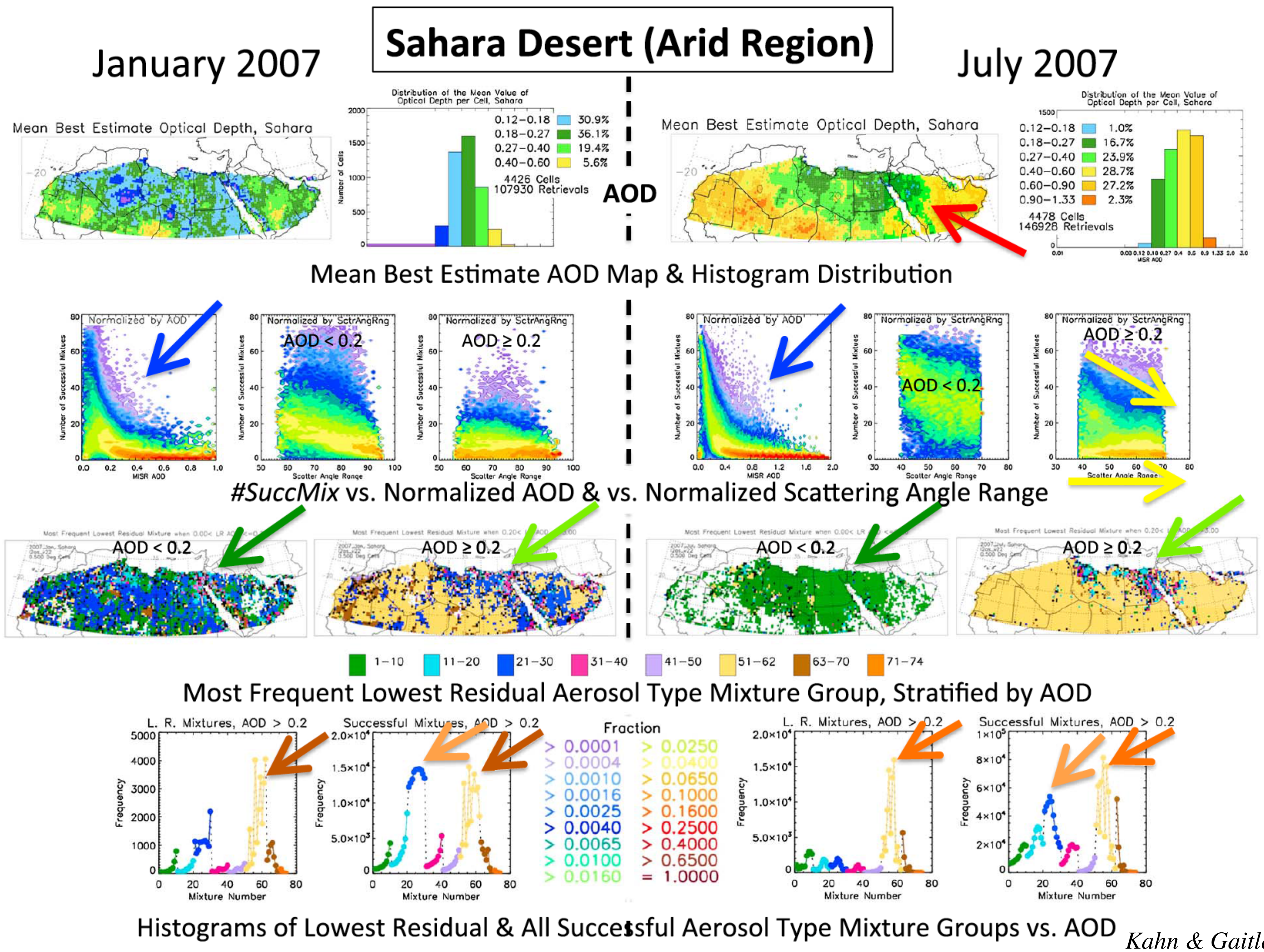
  -- ***Effective radius*** (r_e) and ***variance*** (σ) [two modes – ***issue with def. of "modes"***]

  -- ***Single-scattering albedo*** (*SSA*) [for AOD_440 > 0.4; AERONET SZA > 50˚]

  -- ***Sphericity*** ("*%Sph.*") [for AERONET ***ANG*** < 1.0 only – few coincidences w/AOD>0.2]

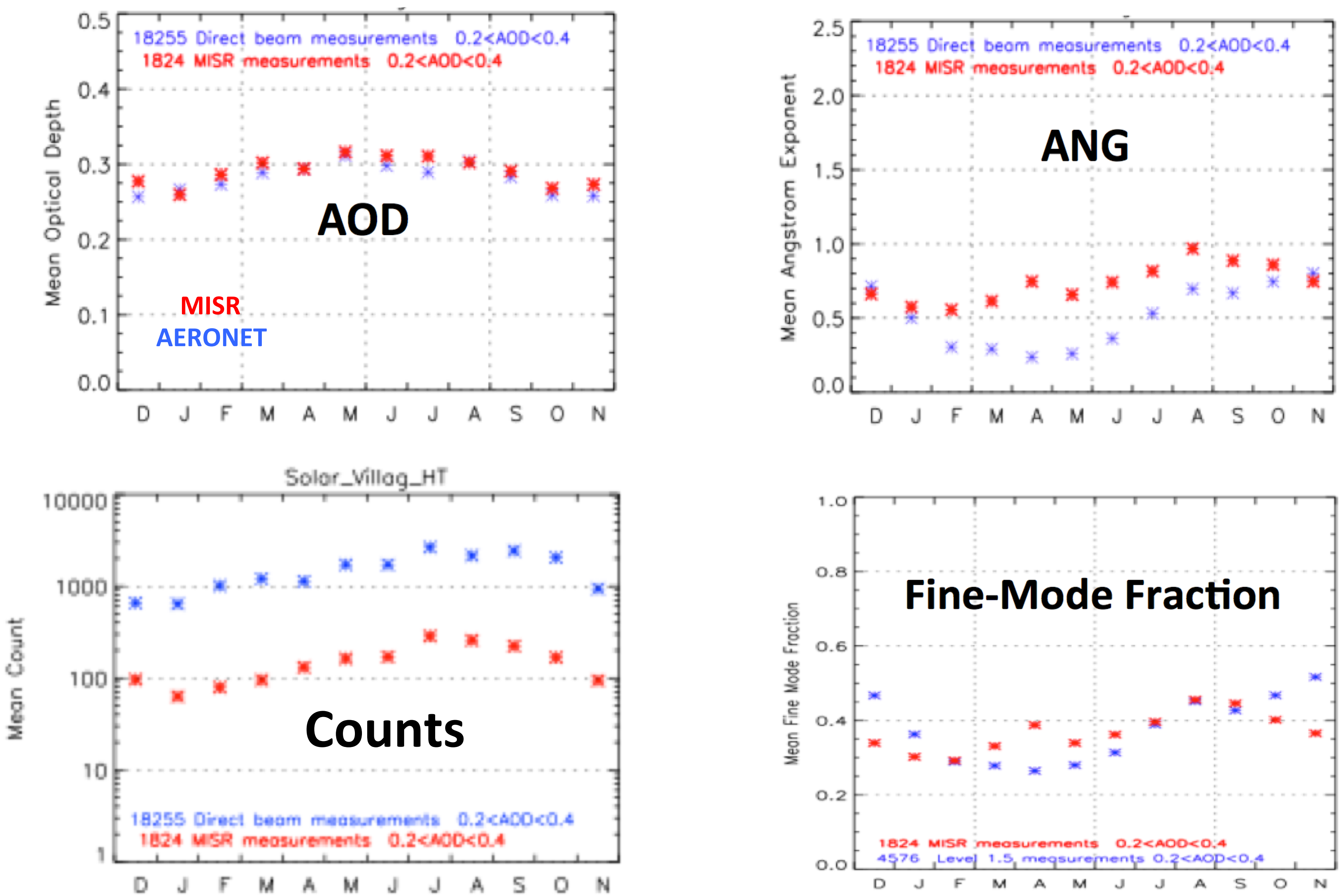
Kahn & Gaitley, JGR, 2015

MISR Aerosol Type Discrimination



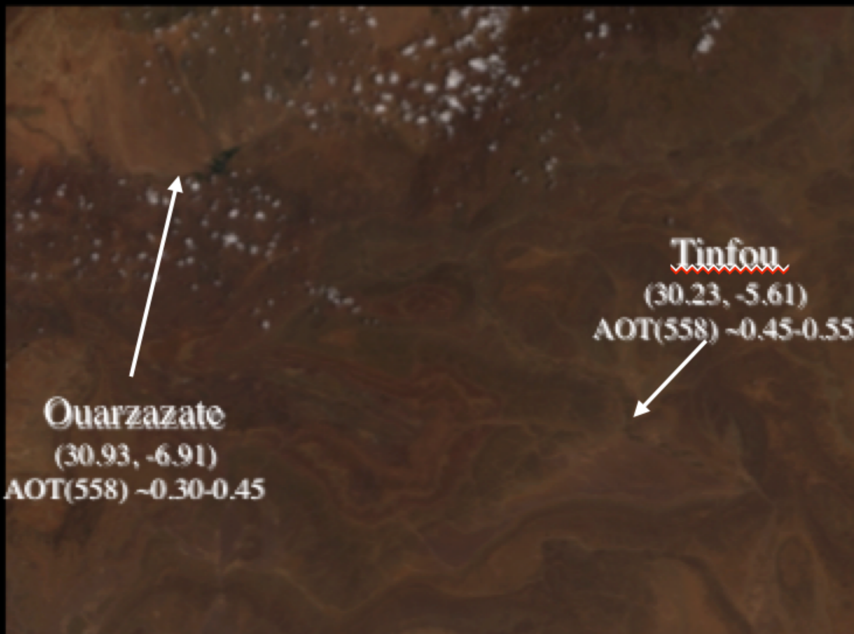
Kahn & Gaitley JGR 2015

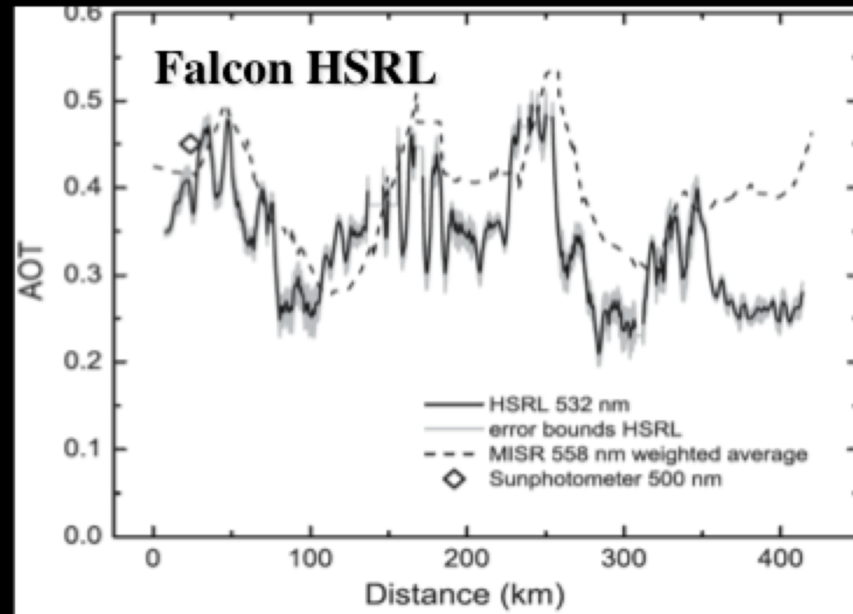
Statistical Comparisons with AERONET – Solar Village



Kahn & Gaitley JGR 2015

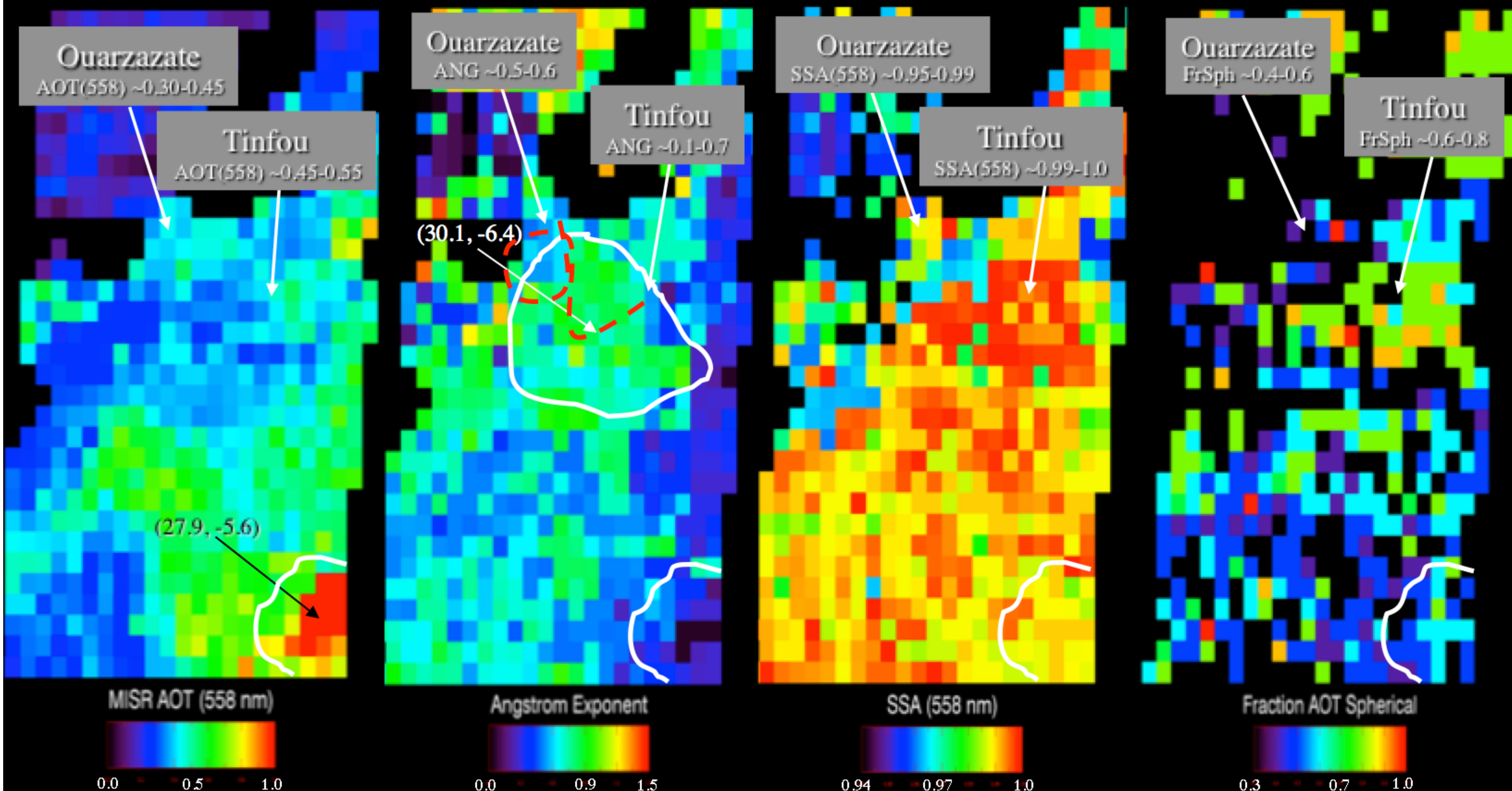
SAMUM Campaign Morocco – June 04, 2006





MISR SAMUM Aerosol Air Masses (V19)

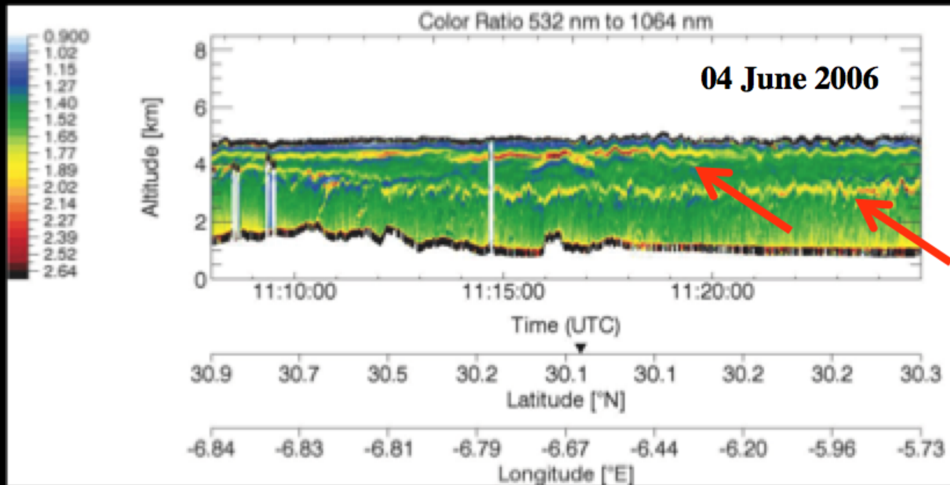
04 June 2006 Orbit 34369, Path 201, Blocks 65-68, 11:11 UTC



- A **dust-laden density flow in the SE** corner of the MISR swath
- **High SSA, ANG** & **Fraction Spherical** region SE of Quarzazate, includes Zagora

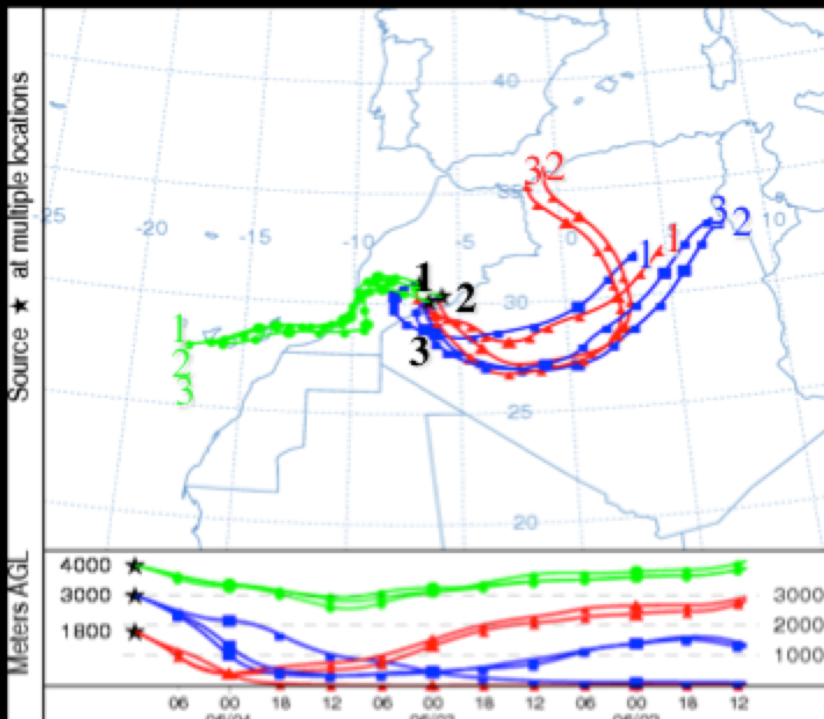
Kahn et al., Tellus 2009

MISR SAMUM Aerosol Air Mass Validation



Falcon F-20 HSRL

- Thin layers of small, bright pollution particles



NOAA/HYSPLIT Back Trajectories

-Source in N Algeria for sites 2, 3 (in the highlighted area) but not 1 (outside it).

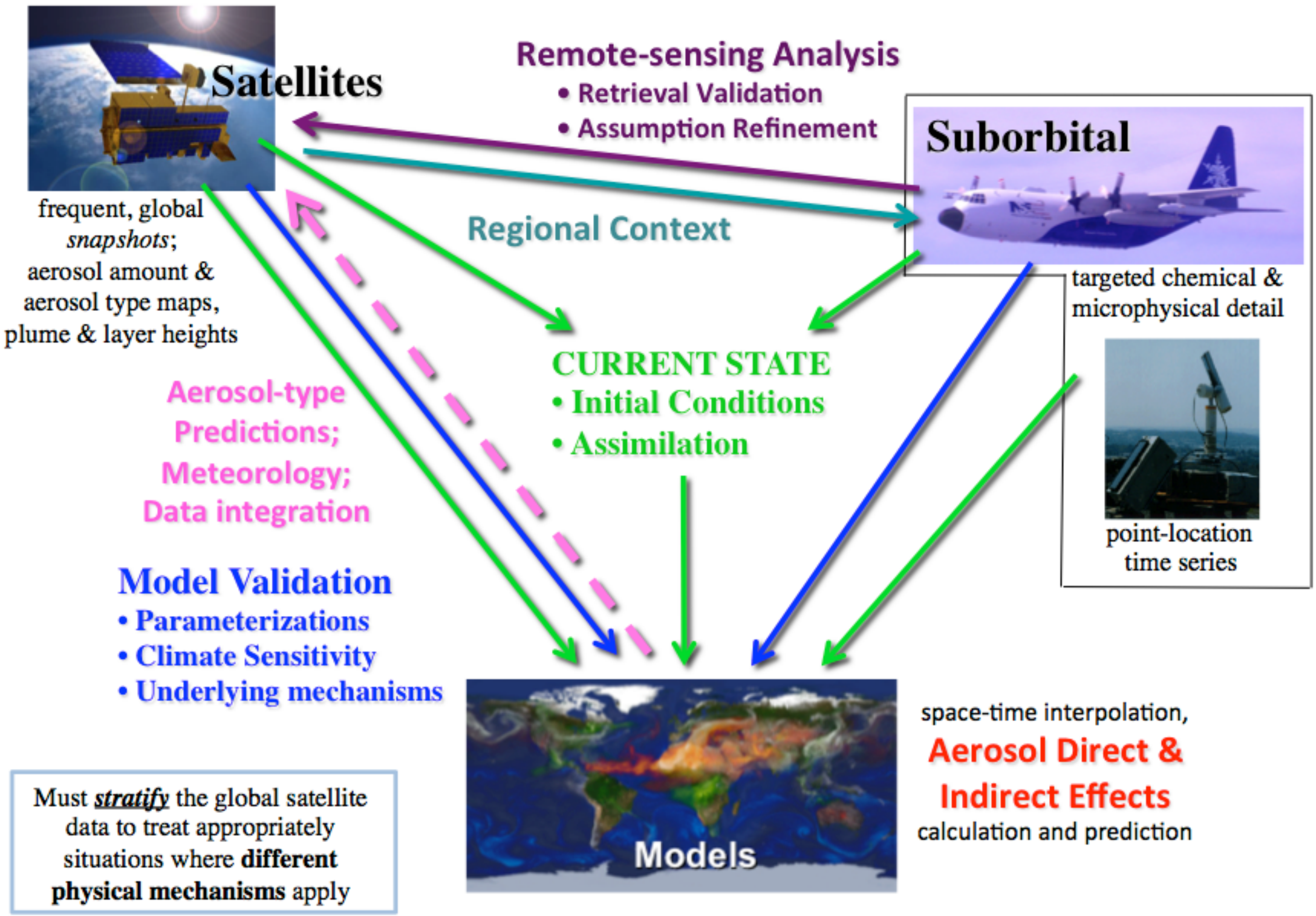
Kahn et al., Tellus 2009

Key Attributes of the MISR **Version 22** Aerosol Product

- **AOT Coverage** – ***Global but limited sampling*** on a monthly basis
- **AOT Accuracy** – Maintained even when particle property information is poor
- **Particle Size** – ***~3 groupings reliably***; quantitative results vary w/conditions
- **Particle Shape** – ***spherical vs. non-spherical robust***, except for coarse dust
- **Particle SSA** – useful for ***qualitative*** distinctions
- **Aerosol Type Information** – diminished when ***AOT < 0.15*** or 0.2
- **Particle Property Retrievals** – ***improvement expected*** w/algorithm upgrades
- **Aerosol Air-mass Types** – ***more robust*** than individual properties

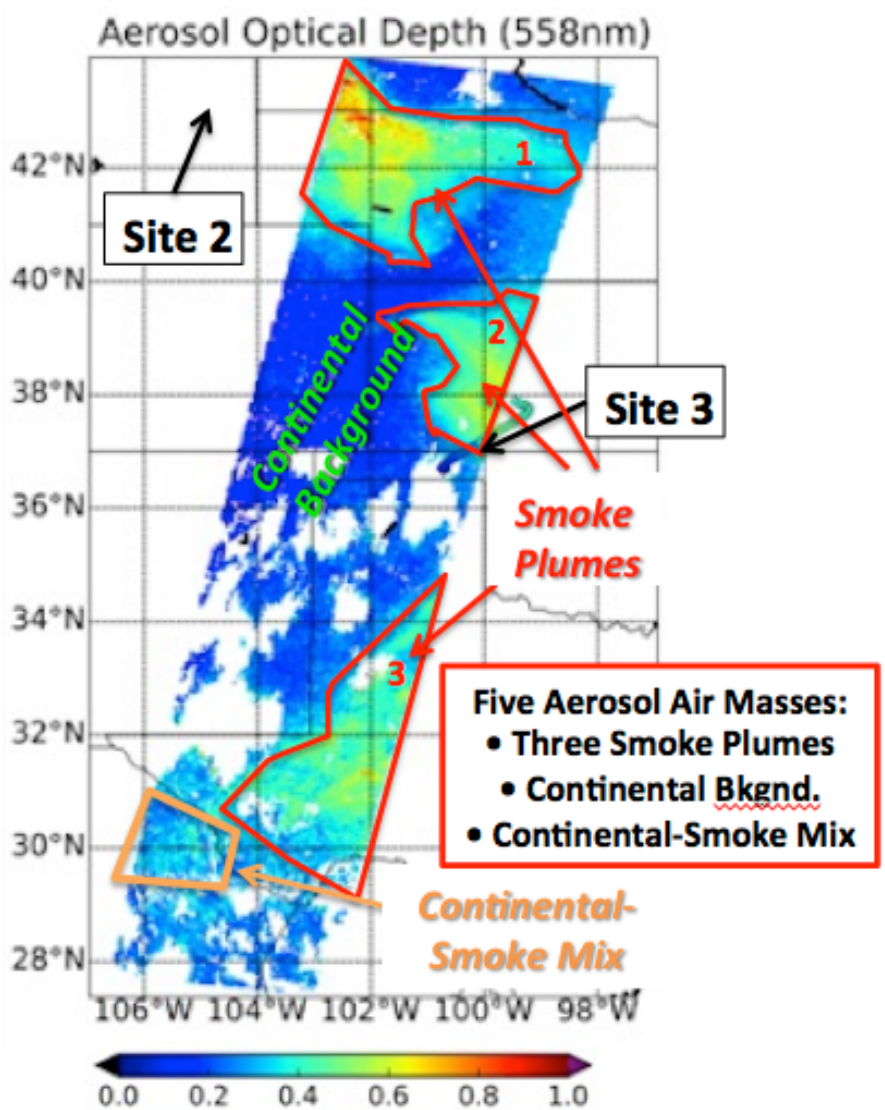
PLEASE READ THE QUALITY STATEMENT!!!

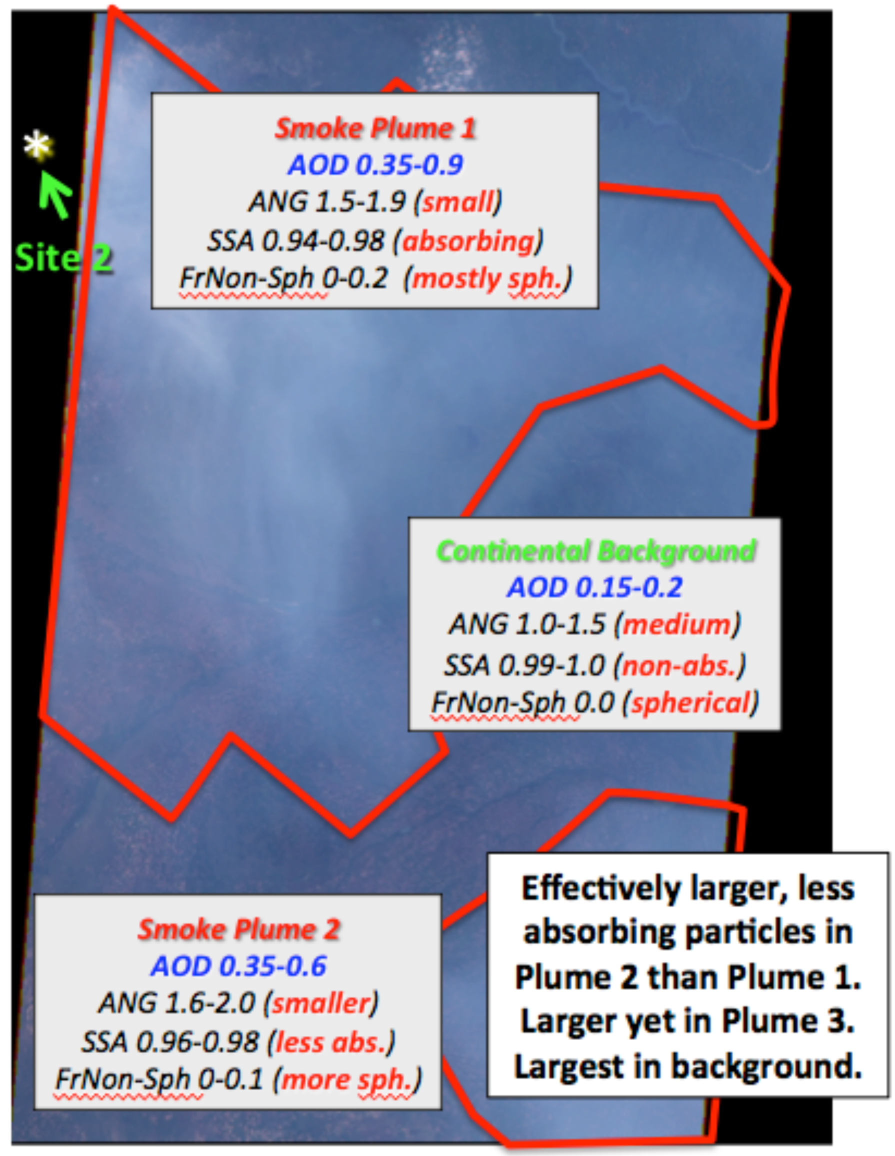
… and more details are in publications referenced therein



Adapted from: Kahn, Survy. Geophys. 2012

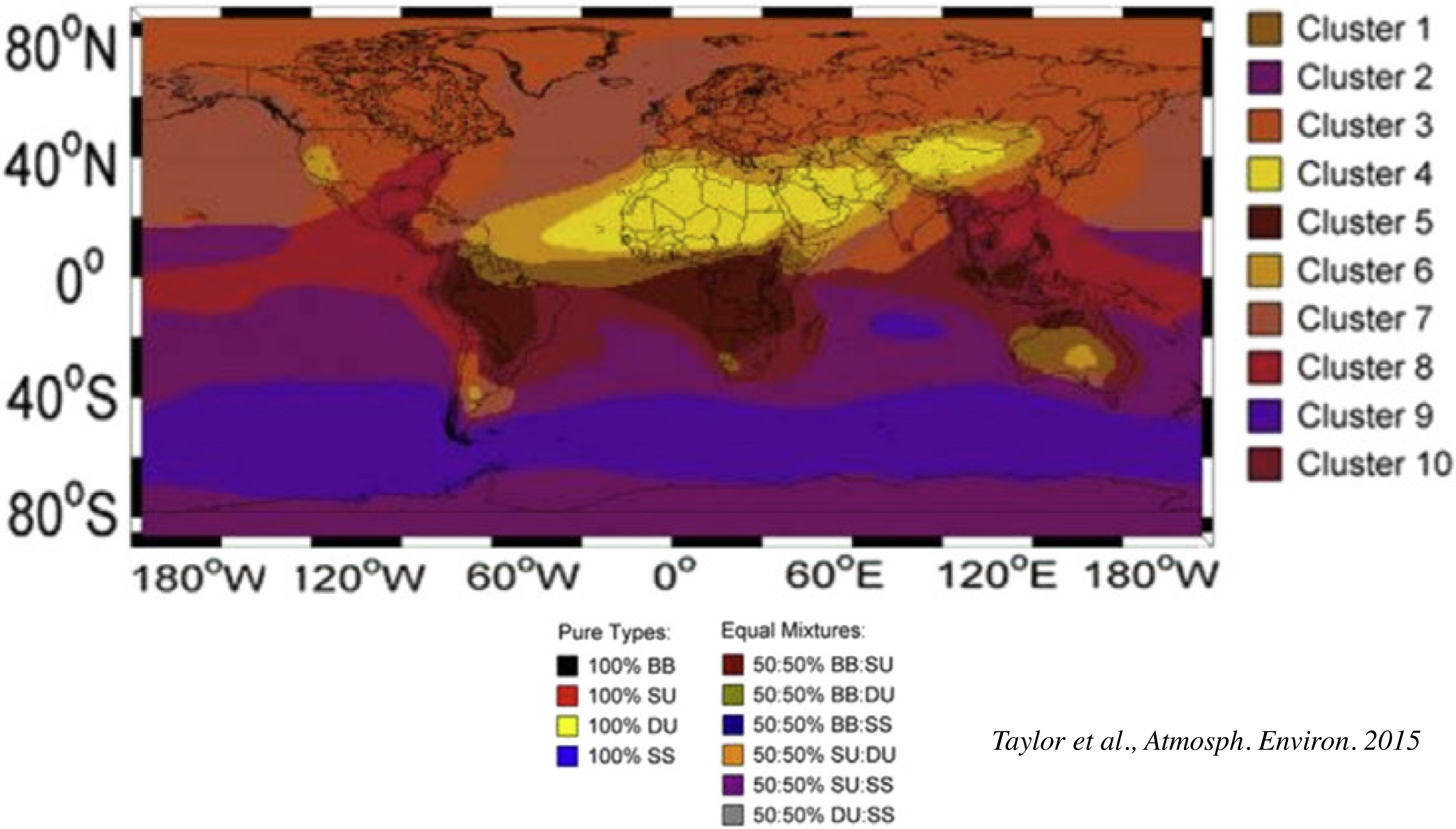
SEAC^{4}RS – MISR Overview 19 August 2013





Passive-remote-sensing ***Aerosol Type*** is a ***Total-Column-Effective***, ***Categorical*** variable!!

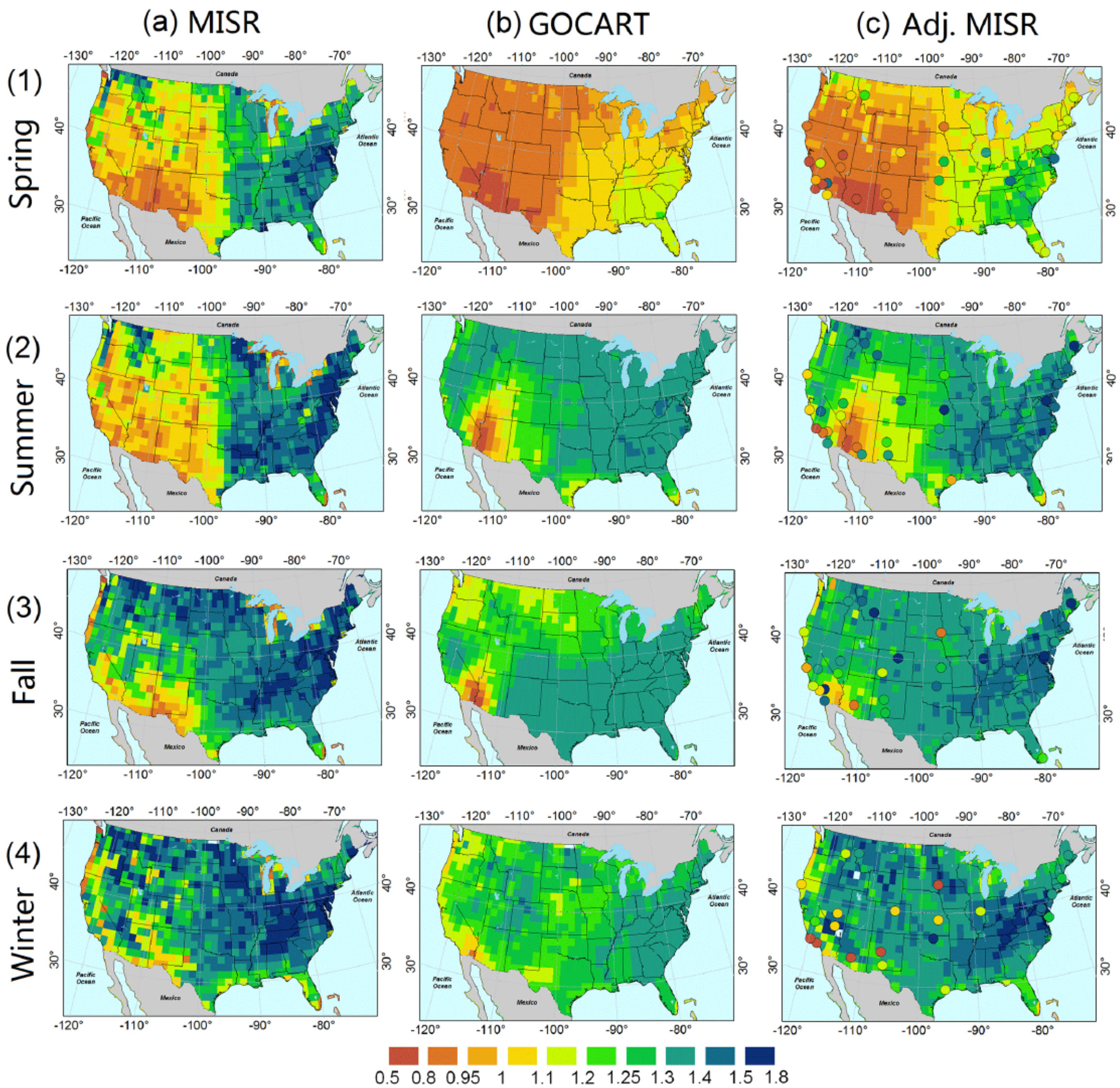
Model-Based Aerosol-Type



Taylor et al., Atmosph. Environ. 2015

Where remote-sensing data are ambiguous, can ***use a model to weights the options***

MISR *ANG*, *AAOD* Results ***Constrained by GoCART Model***



ANG

$$\mathrm{Diff}_{\mathrm{ANG}} = |\alpha_{\mathrm{MISR}} - \alpha_{\mathrm{GOCART}}| \le \varepsilon_{\mathrm{ANG}}$$

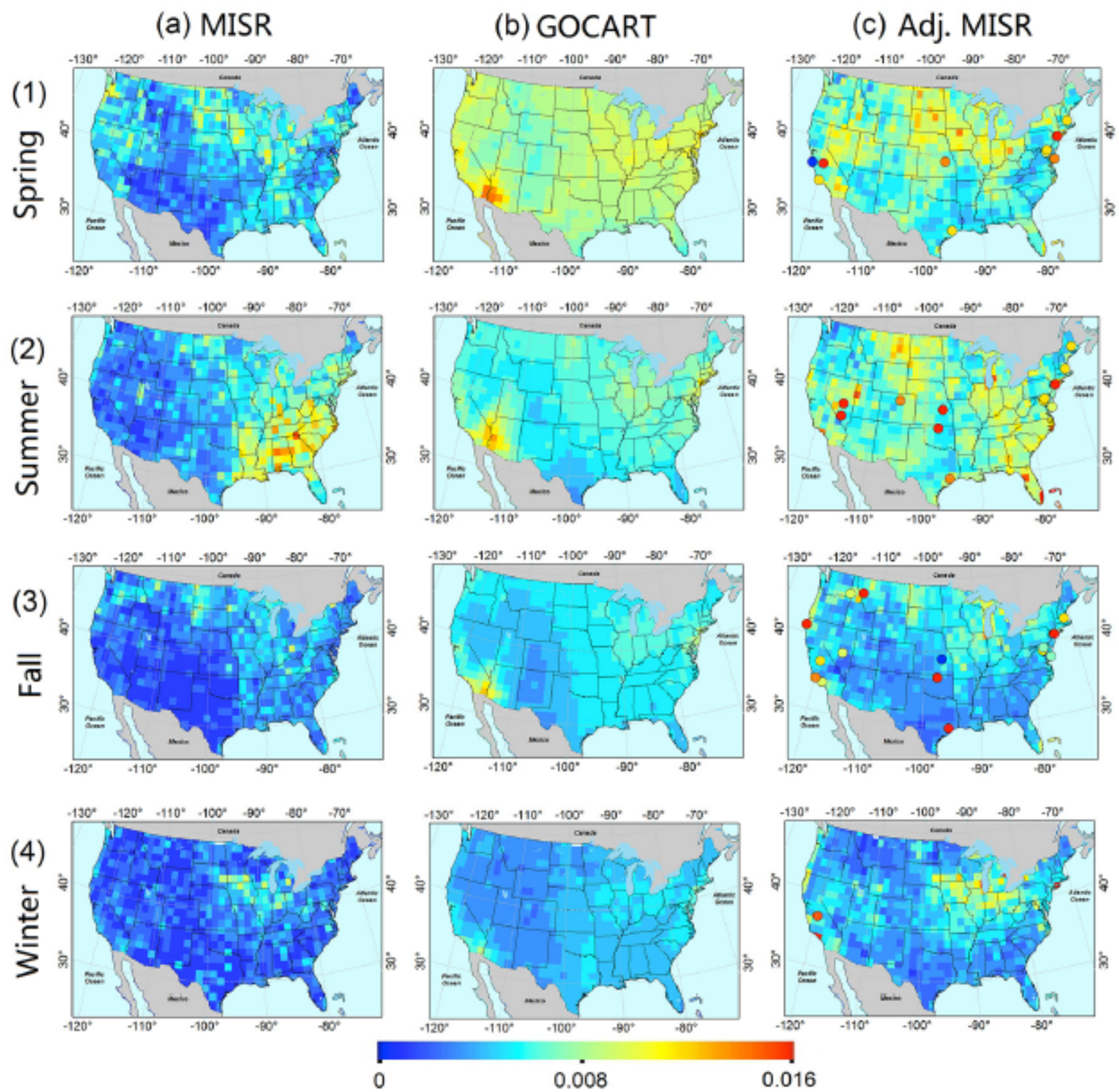
$$\mathrm{Diff}_{\mathrm{AAOD}} = |\mathrm{Fraction}_{\mathrm{MISR\_AAOD}} - \mathrm{Fraction}_{\mathrm{GOCART\_AAOD}}| \le \varepsilon_{\mathrm{AAOD}}$$

Four years of data (2006-2009)
Seasonally averaged

Shenshen Li et al. AMT 2015

Where remote-sensing data are ambiguous, can ***use a model to weights the options***

MISR *ANG*, *AAOD* Results *Constrained by GoCART Model*



AAOD

$$\mathrm{Diff}_{\mathrm{ANG}} = |\alpha_{\mathrm{MISR}} - \alpha_{\mathrm{GOCART}}| \le \varepsilon_{\mathrm{ANG}}$$

$$\mathrm{Diff}_{\mathrm{AAOD}} = \left|\mathrm{Fraction}_{\mathrm{MISR\_AAOD}} - \mathrm{Fraction}_{\mathrm{GOCART\_AAOD}}\right| \le \varepsilon_{\mathrm{AAOD}}$$

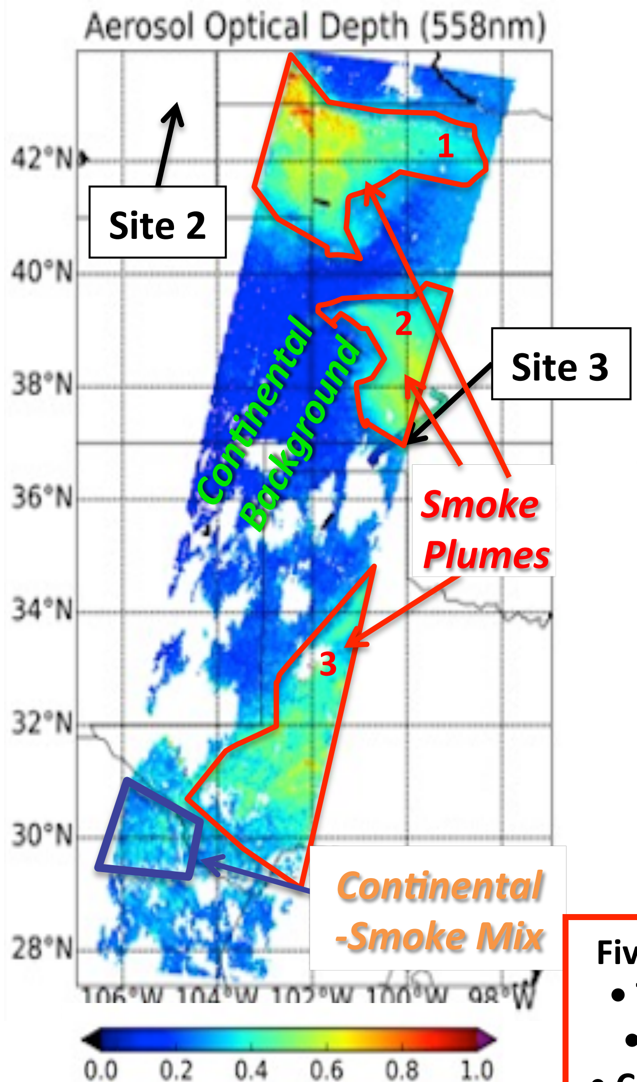
Four years of data (2006-2009)
Seasonally averaged

Shenshen Li et al. AMT 2015

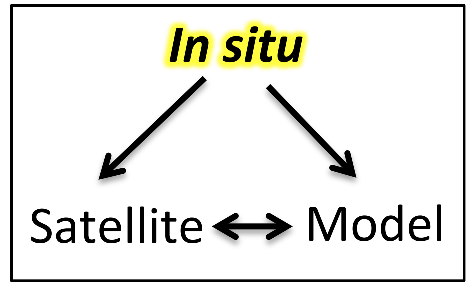
Where remote-sensing data are ambiguous, can ***use a model to weights the options***

A Three-way Street:

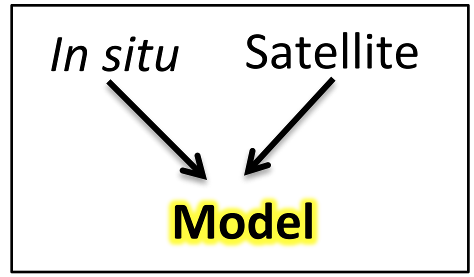
MISR & MODIS Provide Context, SEAC^{4}RS Provides Detail, and Models Compete the Picture



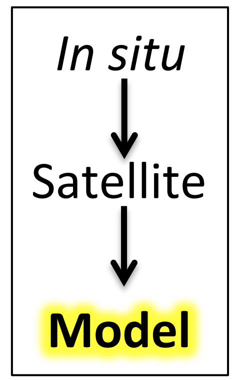
Story 1: ***Aerosol Air Mass Type Validation***



Story 2: ***Upwind Smoke Source & Injection Height***



Story 3: ***Regional Aerosol Characterization***



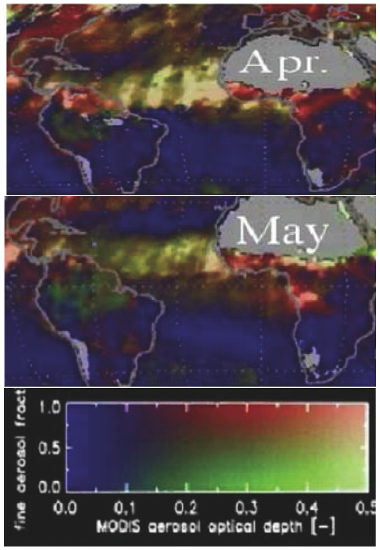
Five Aerosol Air Masses:
- **Three Smoke Plumes**
- **Continental Bkgnd.**
- **Continental-Smoke Mix**

19 August Golden Day

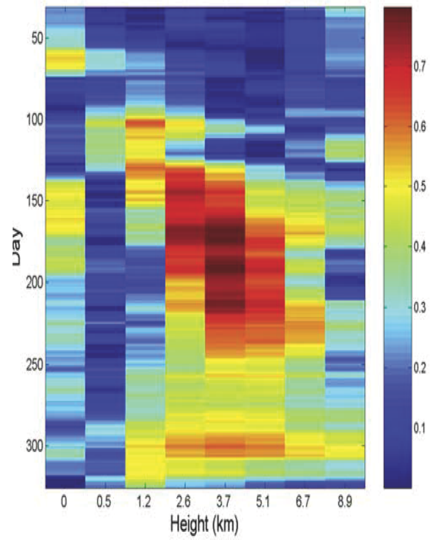
R. Kahn et al., in preparation

Applications –
Transports & Plume Heights

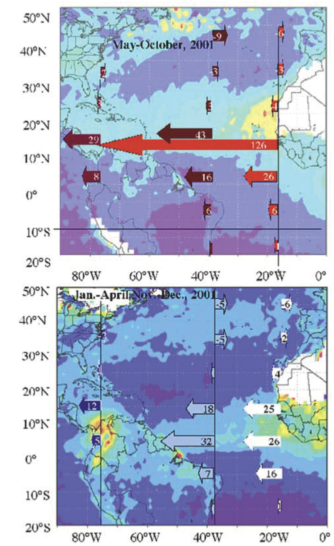
Aerosol Material Fluxes: Atlantic Dust & Asian Pollution



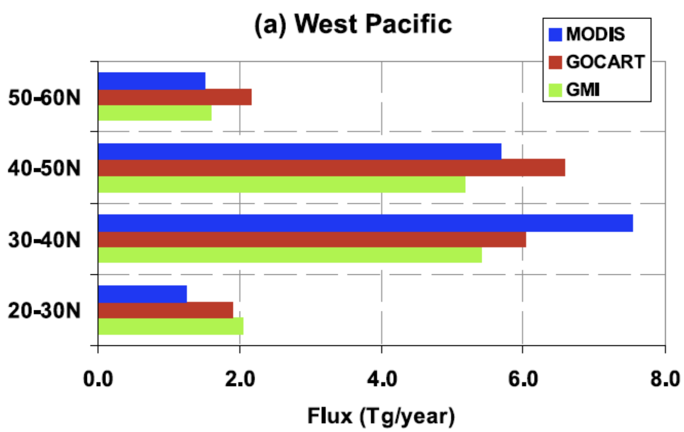
MODIS AOD & Type
Low AOD, **Fine BioBurn**, **Coarse Dust**

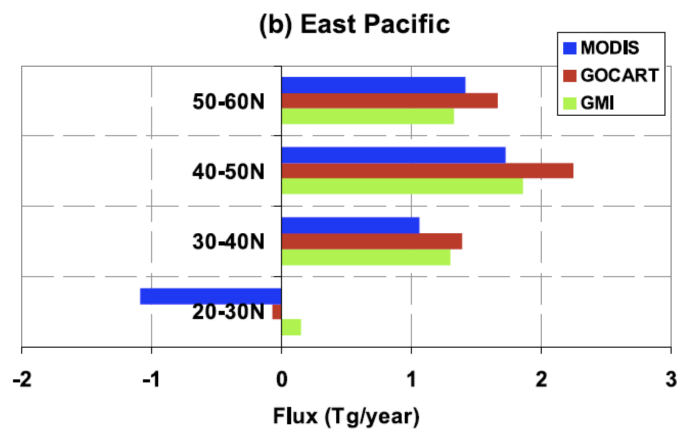


NCEP **W Wind** - MODIS **AOD**
Correlation 2.6-5 km; May-October



Dust Transport Estimate (Tg)
May-October (Top) January-April (Bot)
Kaufman et al., JGR 2005

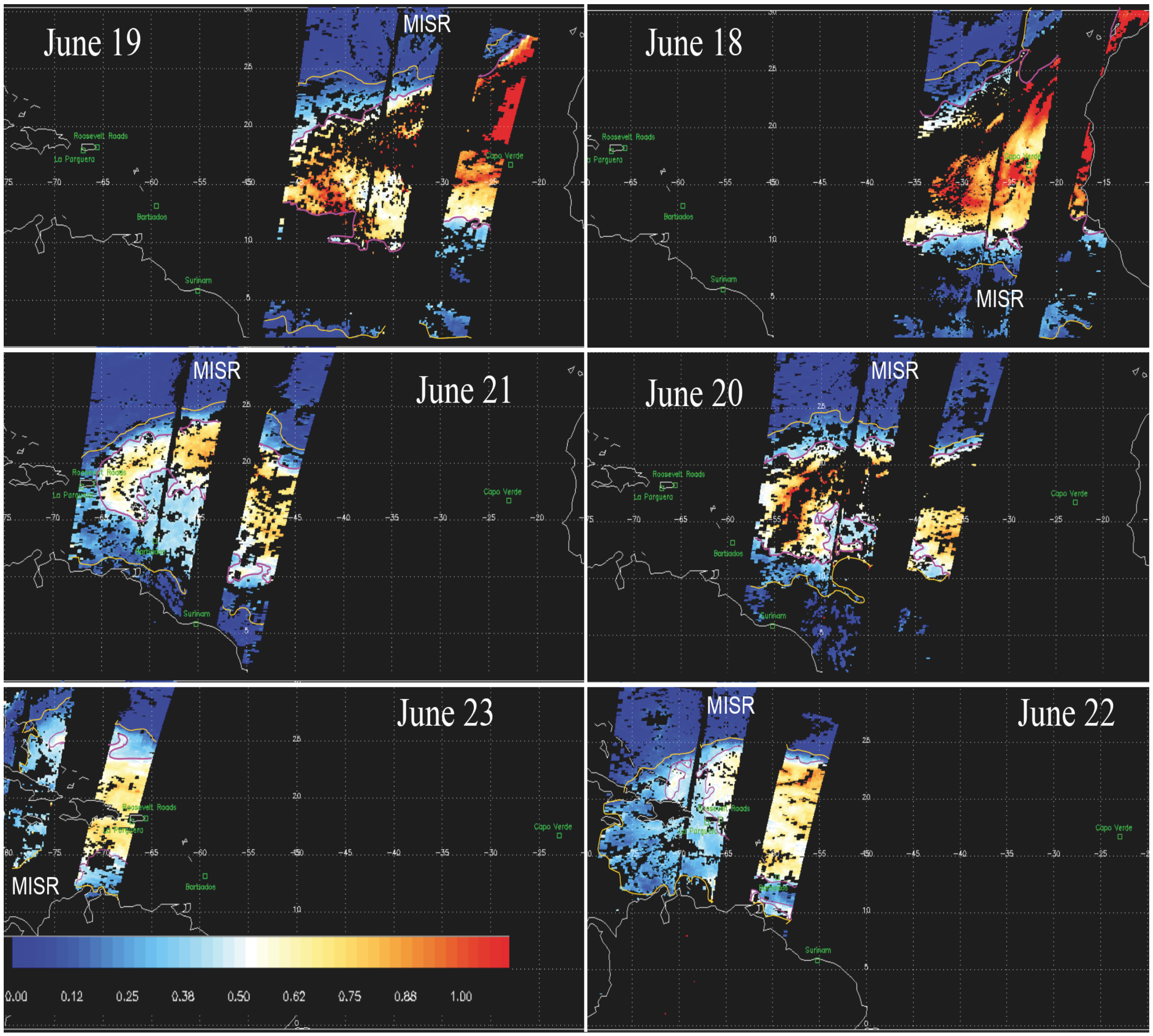




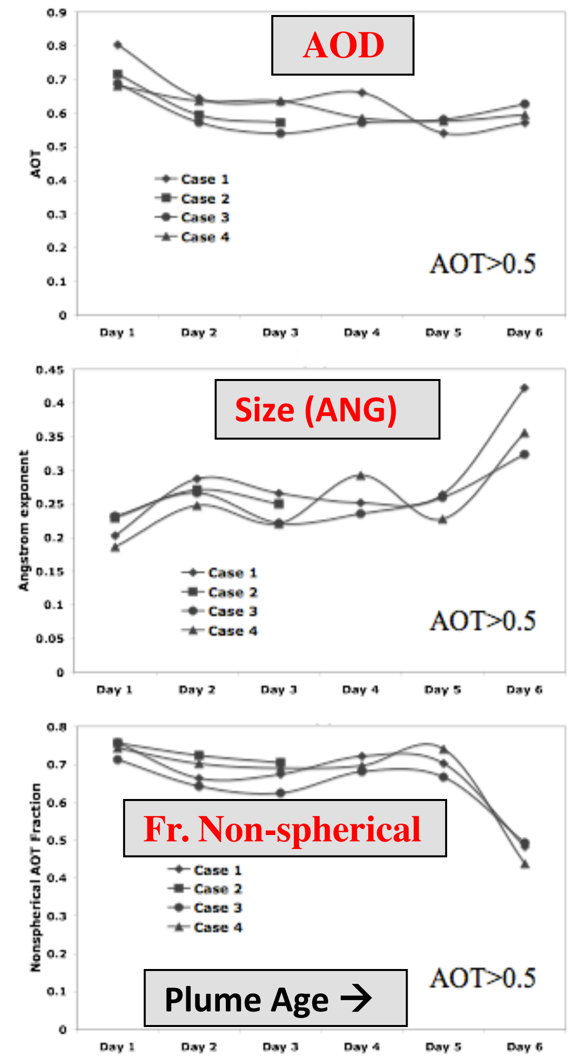
MODIS AOD & type, **Field Campaign** aerosol properties & vertical distribution, GEOS model winds;
Compared with GOCART and GMI model Fine-particle mass fluxes *Yu et al., JGR 2008*

Constraining Aerosol Sources, Transports, & Sinks

Complementary MISR & MODIS AOD; Saharan Dust Plume over Atlantic June 19-23, 2000

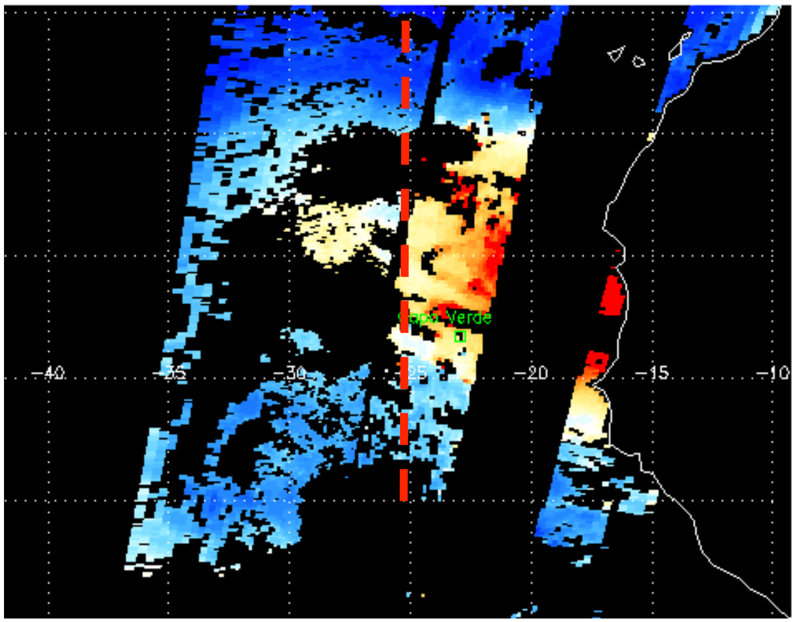


Contours: AOT=0.15 (yellow); AOT=0.5 (purple)

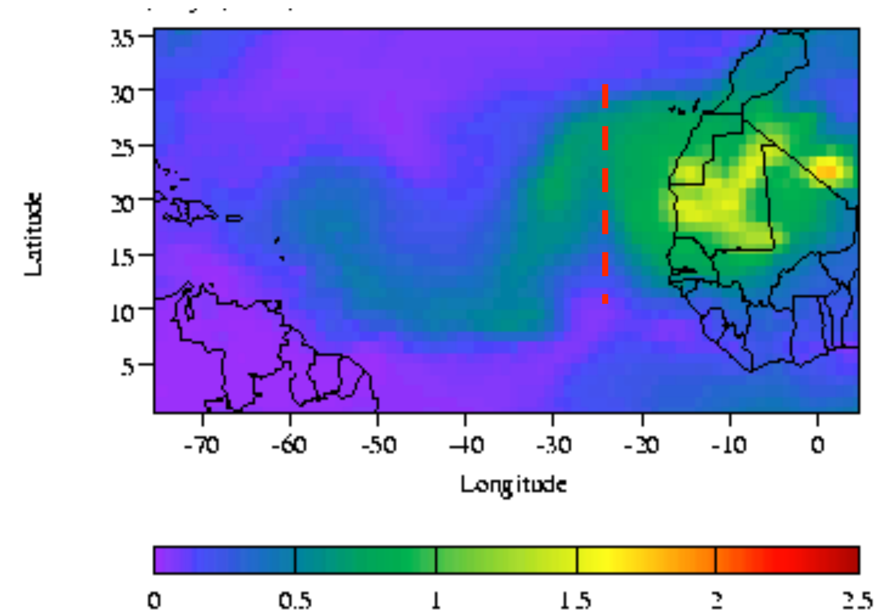


Kalashnikova and Kahn, JGR 2008

MISR-MODIS-NAAPS (July 4, 2000)



MISR and MODIS AOD



NAAPS Dust

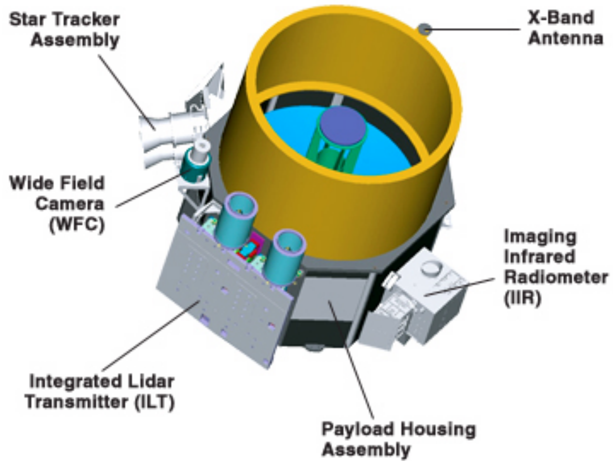
NAAPS dust plume extent predictions:

- **In qualitative agreement with MISR & MODIS**
- **Magnitudes differ… constrains dust Source Strength & Removal Rate**

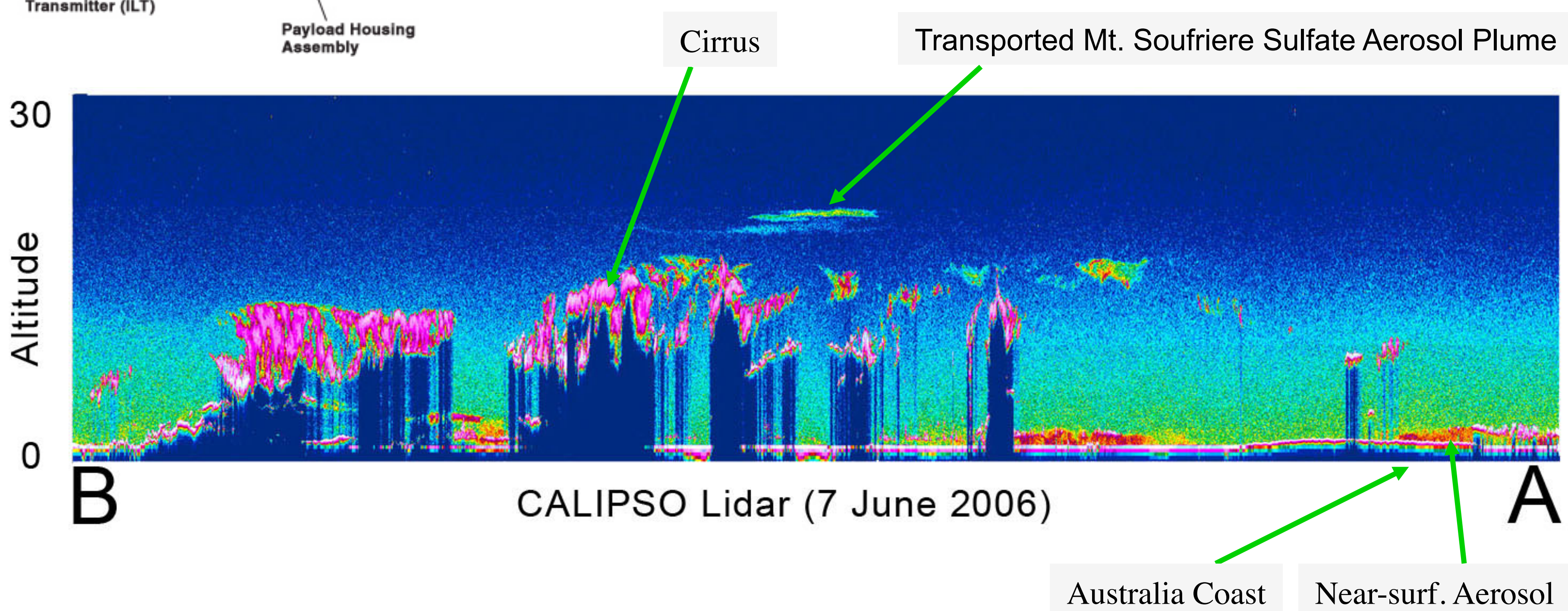
Kalashnikova et al., 2008

CALIPSO Space Lidar

First Light - June 07, 2006

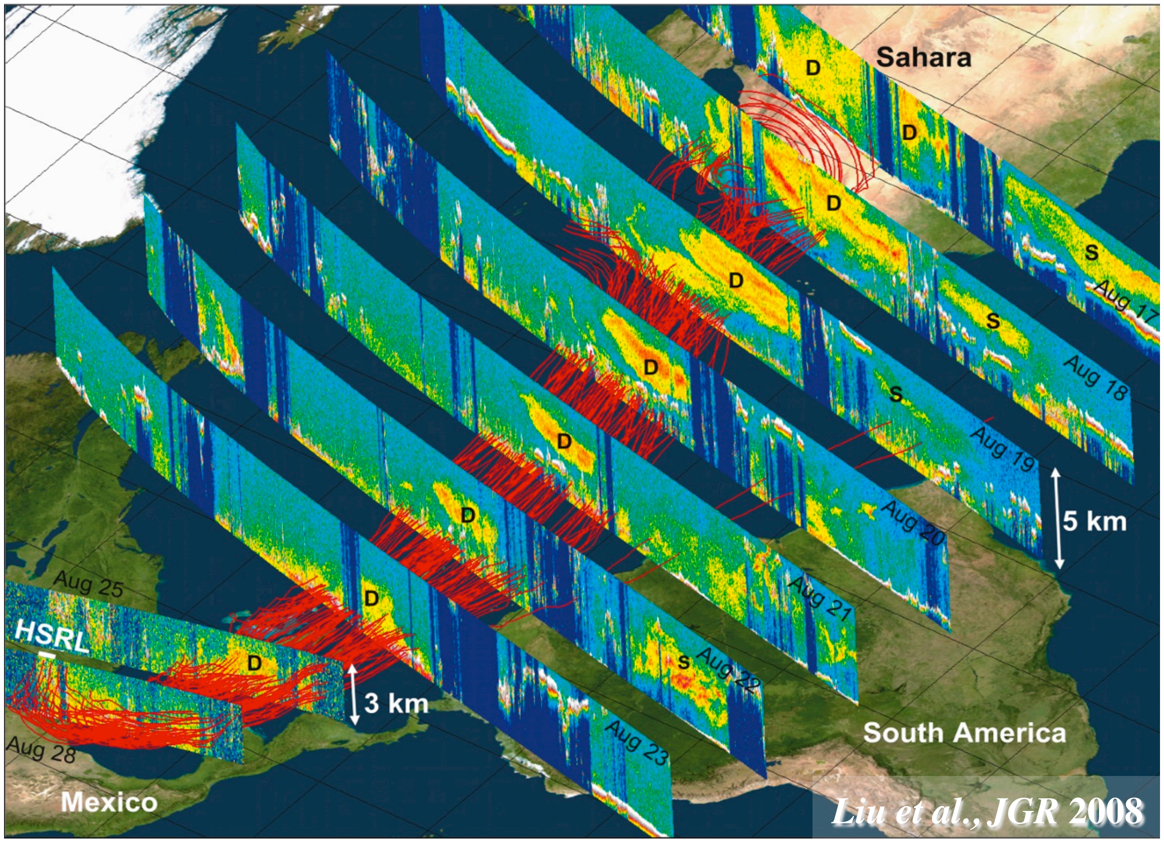


523 and 1064 nm channels; ~100m horizontal resolution



http://www.nasa.gov/mission_pages/calipso/main/index.html

Aerosol Sources, Processing, Transports, Sinks: Lidar + Model

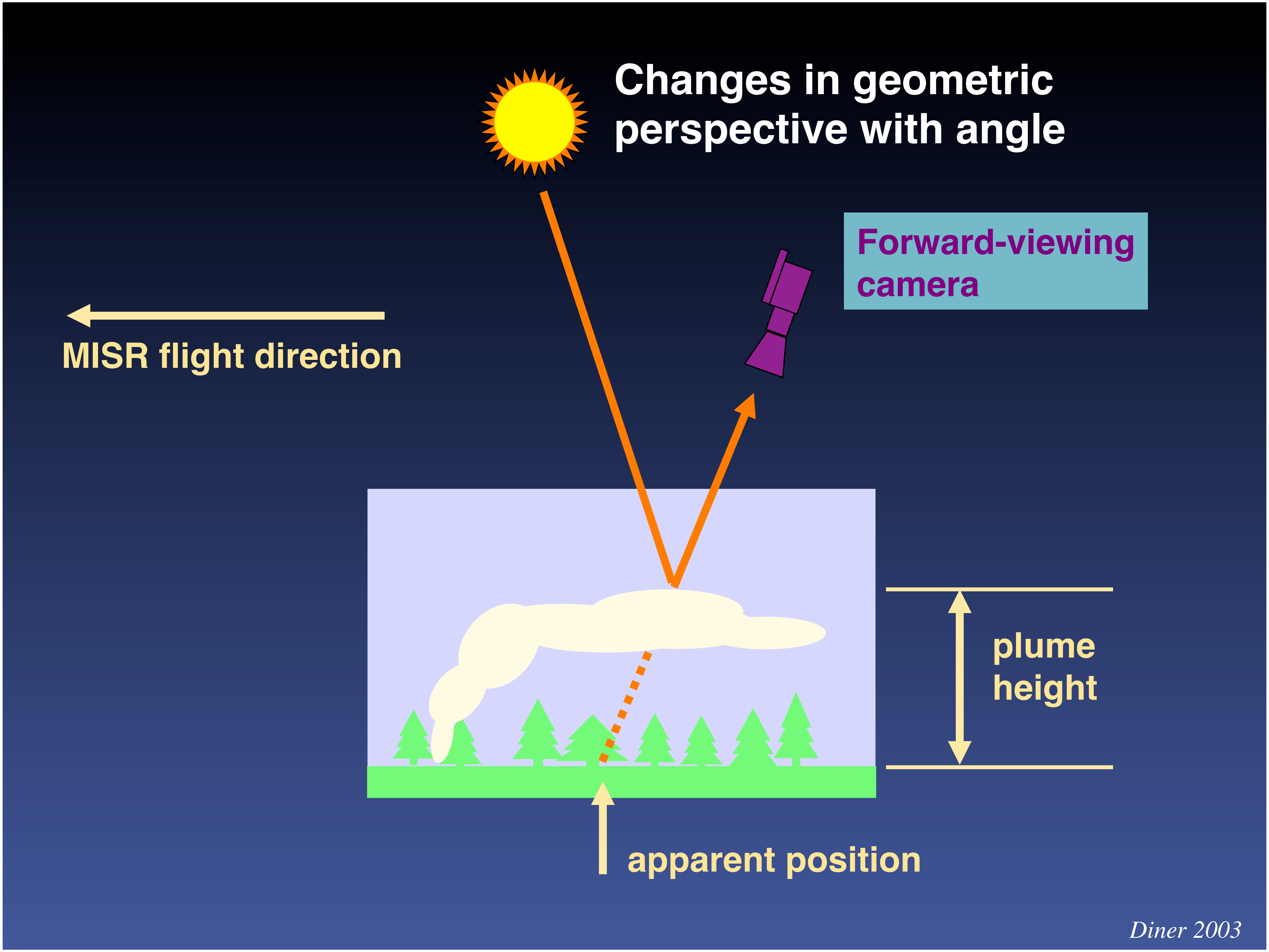


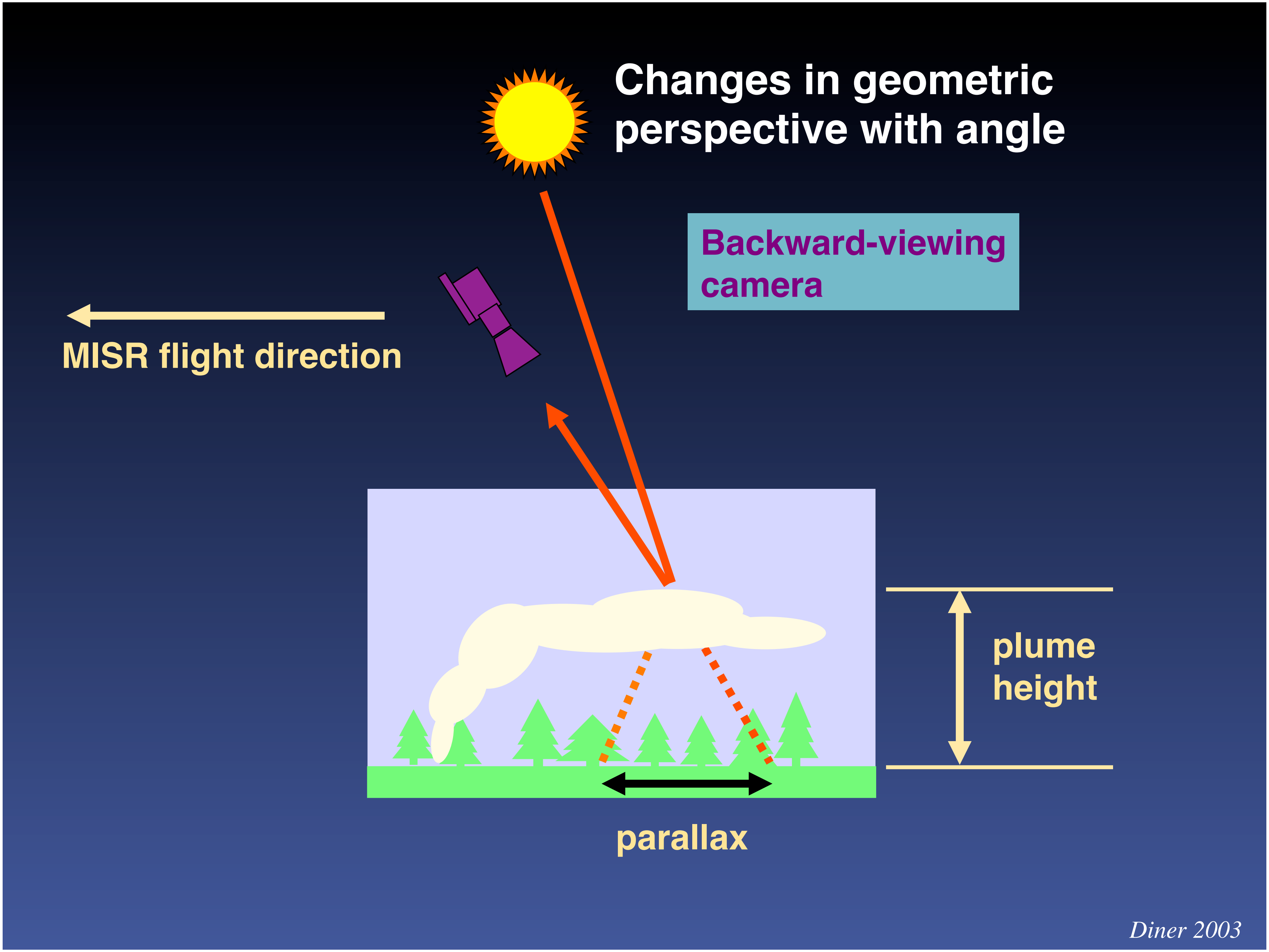
August 2007 Saharan dust "D" and smoke "S" event

mapped by CALIPSO 532 nm backscatter, with superposed model back trajectories and airborne HSRL observations

Piecing together the bigger picture. Consistency requires –

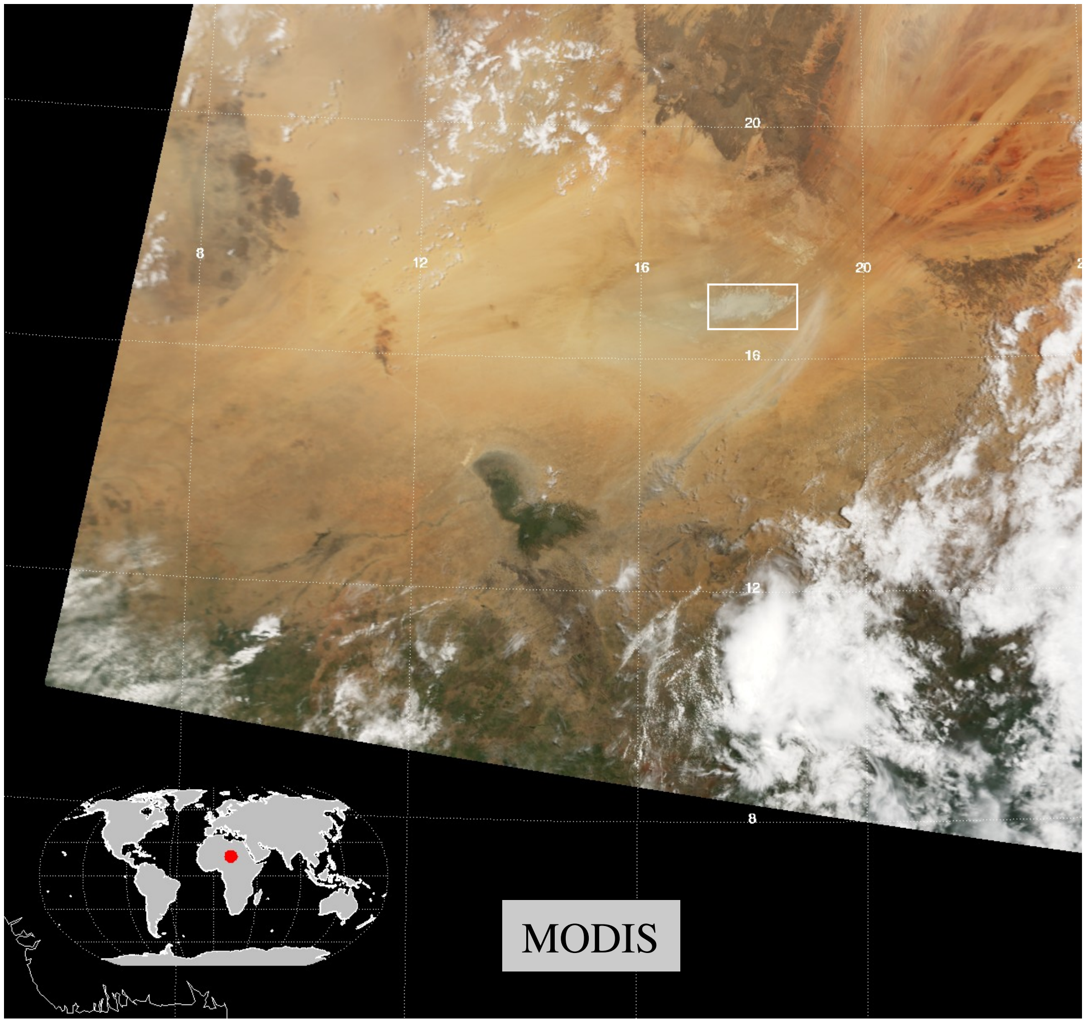
- An understanding of the ***mechanisms*** governing aerosol evolution
- Adequately constrained ***initial & boundary*** conditions

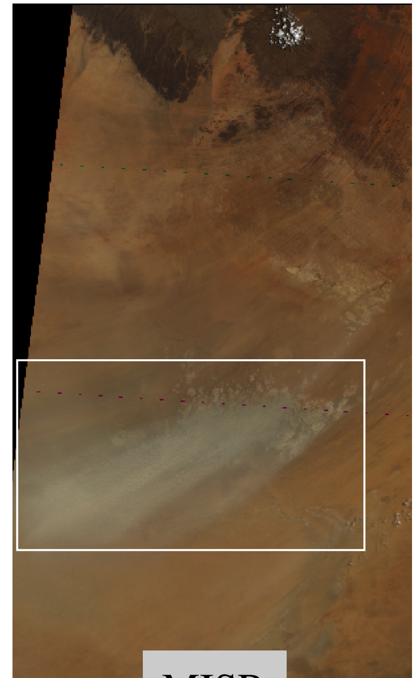

Changes in geometric perspective with angle
Forward-viewing camera
MISR flight direction
plume height
apparent position
Diner 2003

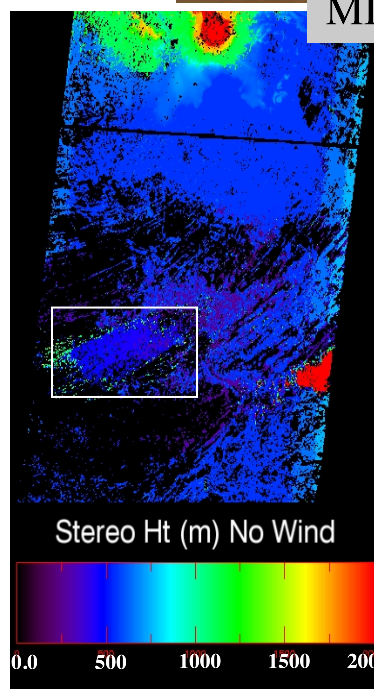

Changes in geometric perspective with angle
Backward-viewing camera
MISR flight direction
plume height
parallax
Diner 2003

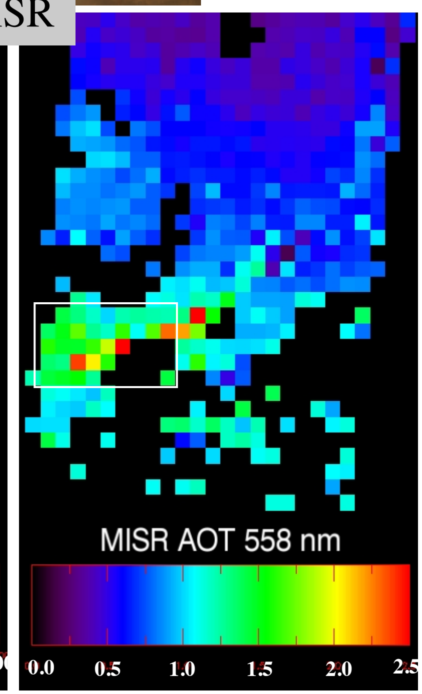
Saharan Dust Source Plume

Bodele Depression **Chad June 3, 2005 Orbit 29038**







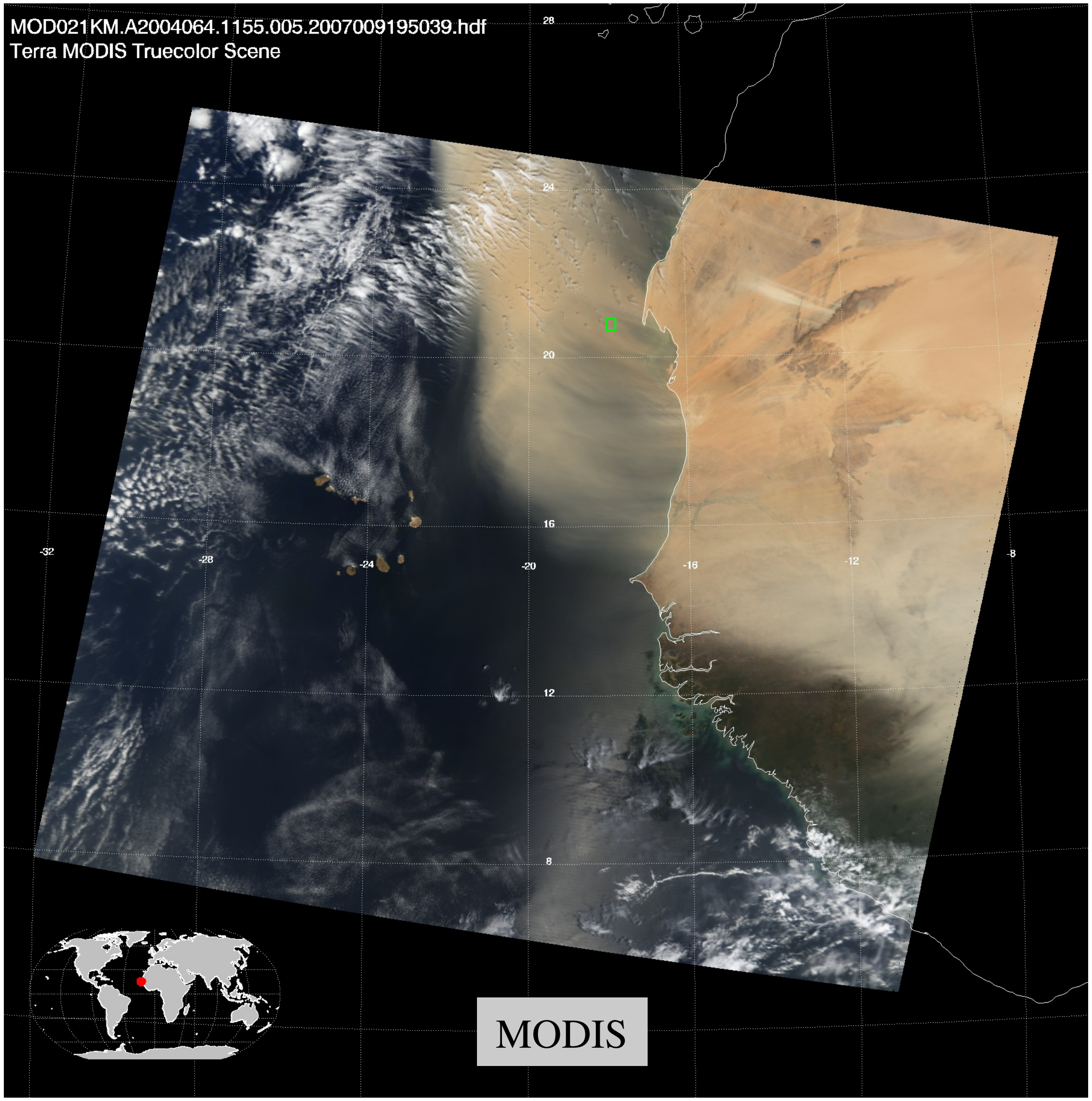


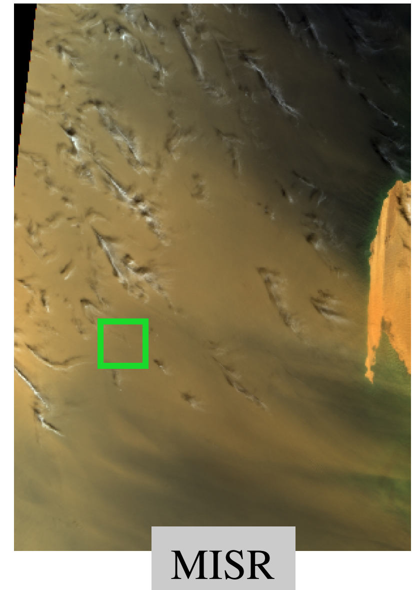
Dust is injected near-surface…

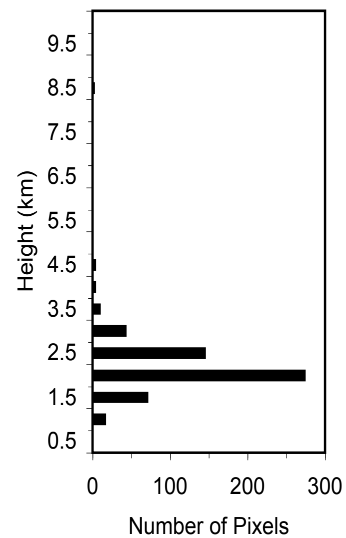
Kahn et al., JGR 2007

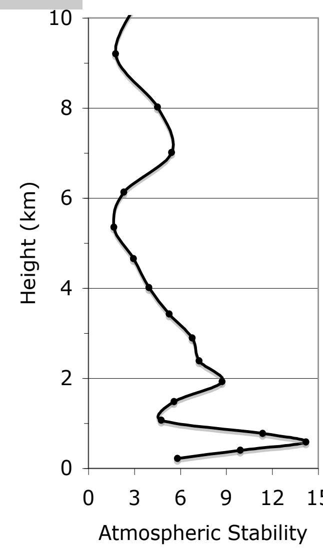
Transported Dust Plume

Atlantic, off Mauritania March 4, 2004 Orbit 22399





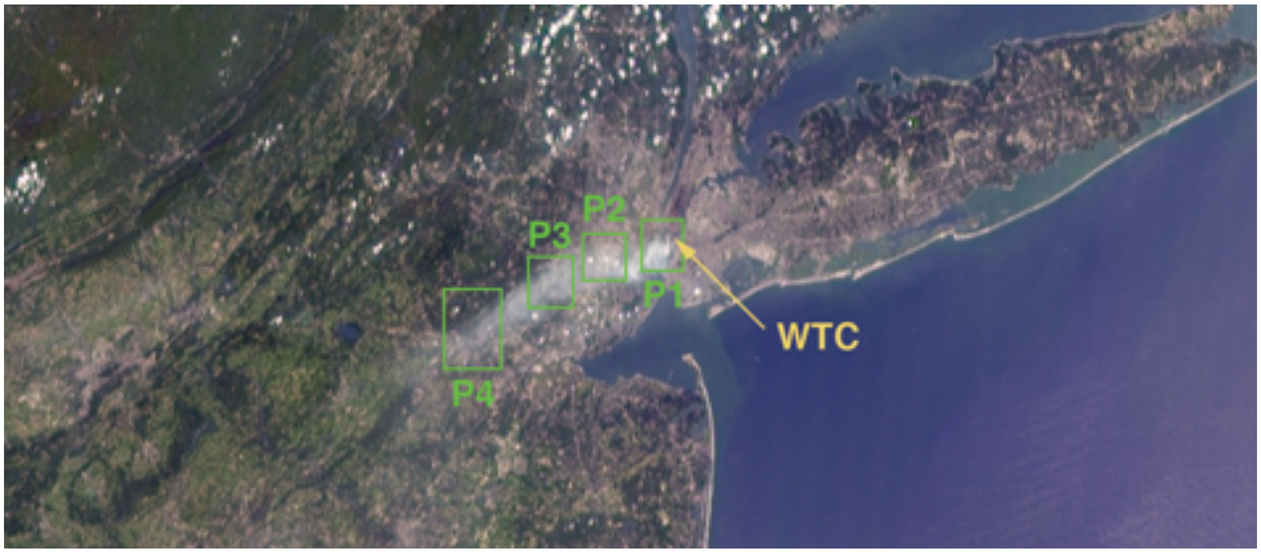




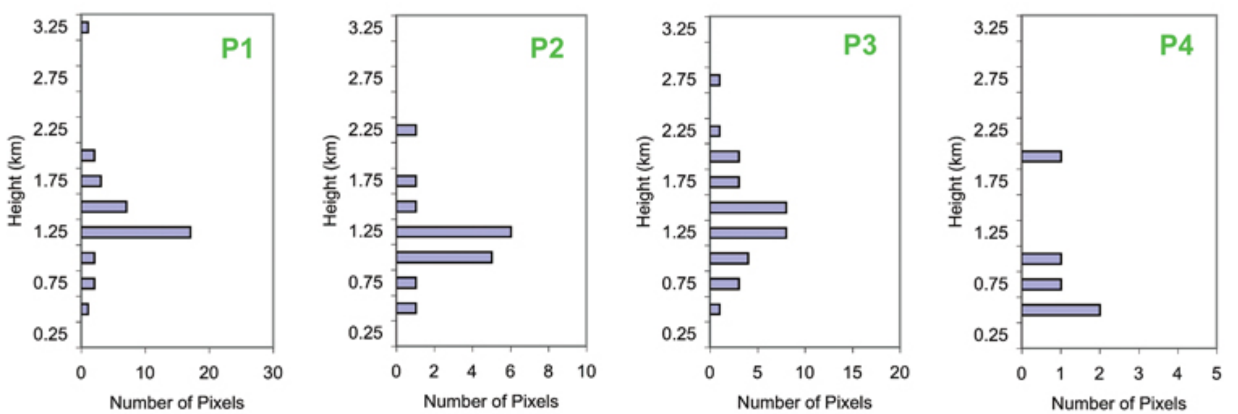
Transported dust finds elevated layer of relative stability…

Kahn et al., JGR 2007

MISR height analysis of World Trade Center plume
12 September 2001



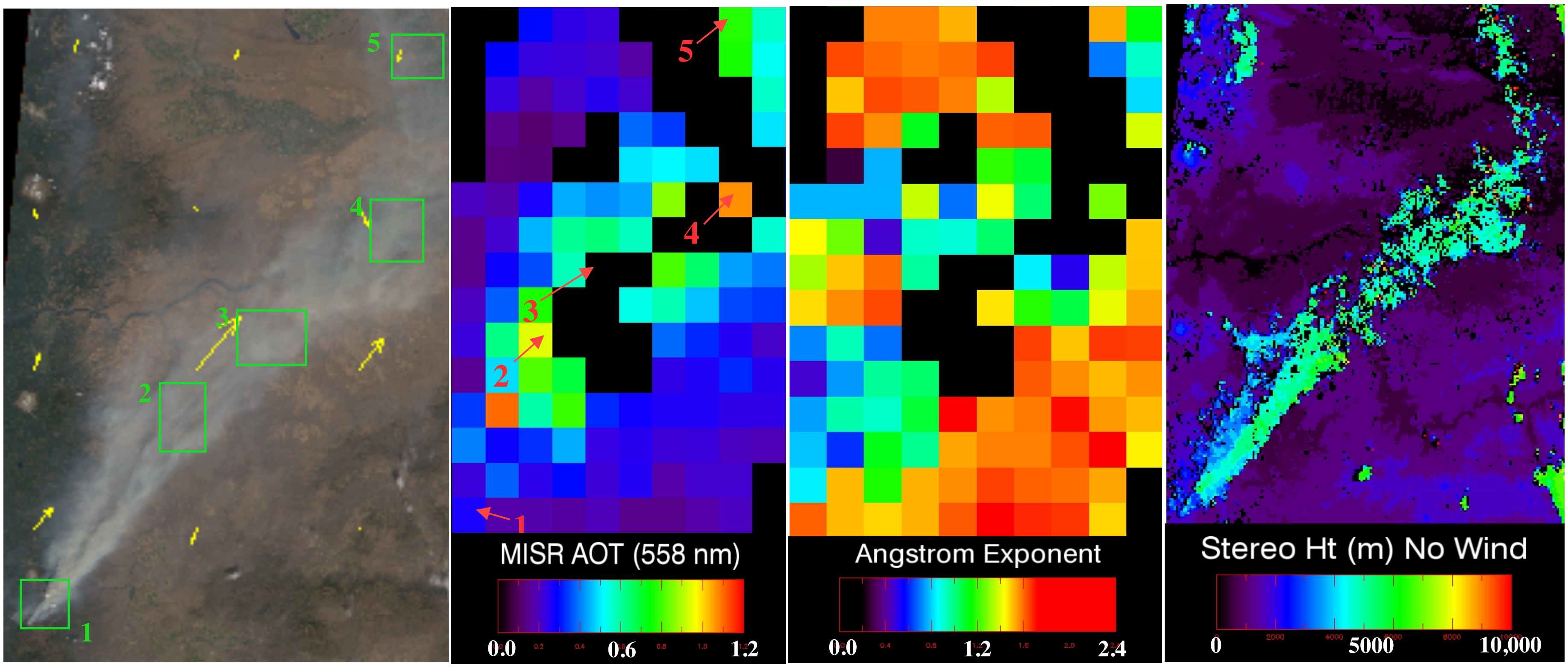
MISR 70º image

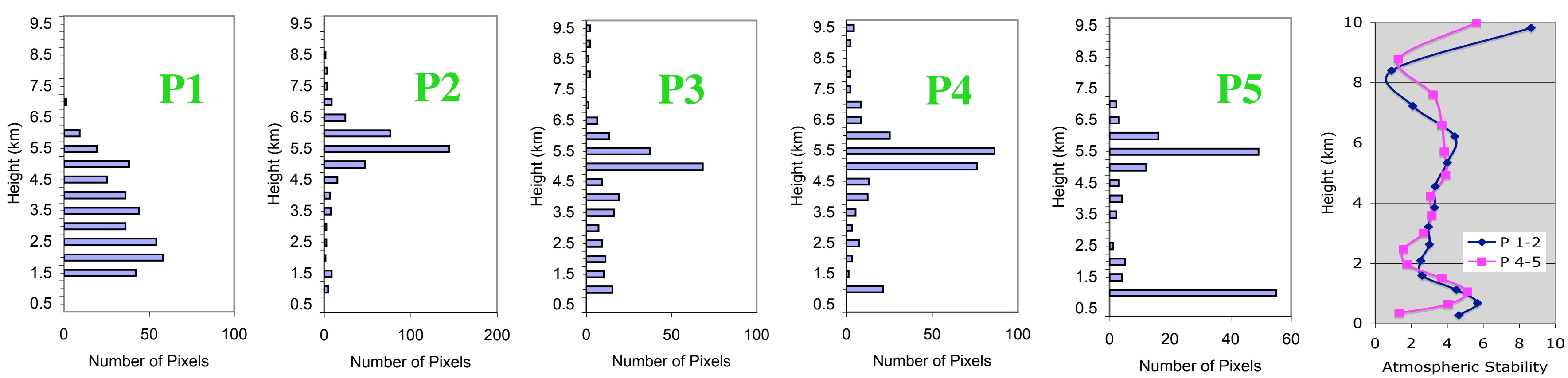


MISR stereo heights of plume patches

Stenchikov et al., *J. Env. Fl. Mech*., 2006

Oregon Fire Sept 04 2003
Orbit 19753 Blks 53-55 MISR Aerosols V17, Heights V13 (no winds)

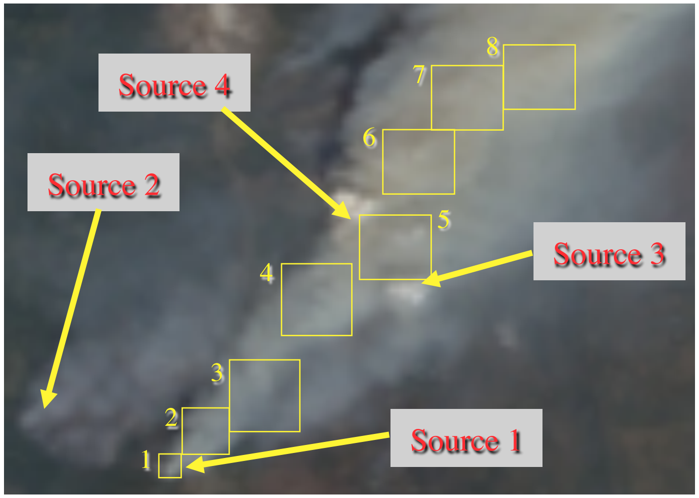




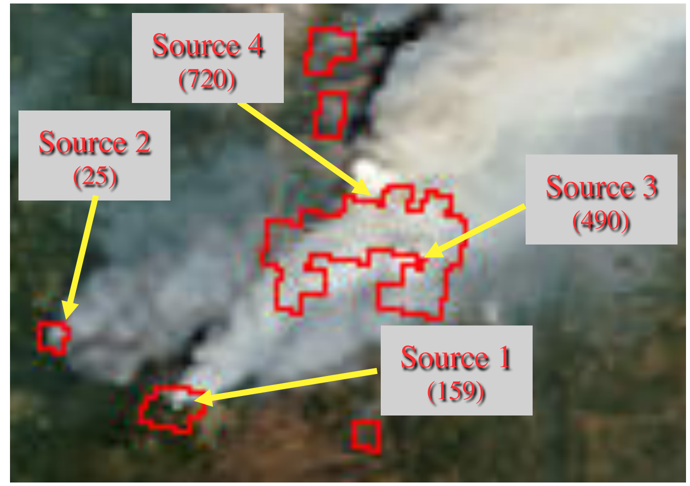
Kahn, et al., JGR 2007

Detail of Wildfire Source Region

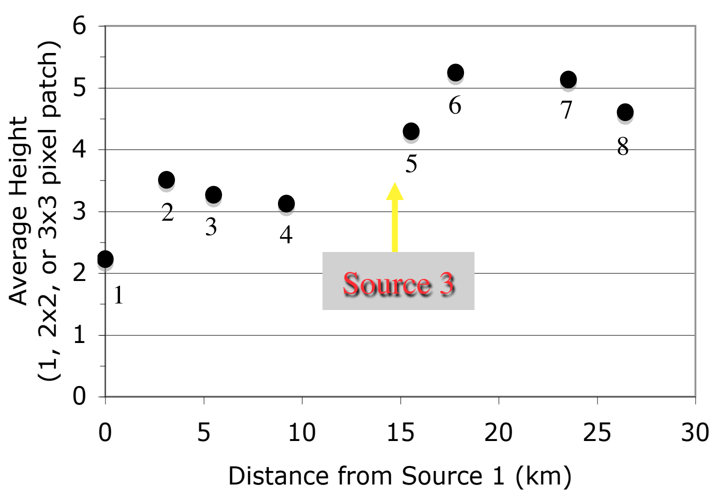
Oregon Fire Sept 04 2003



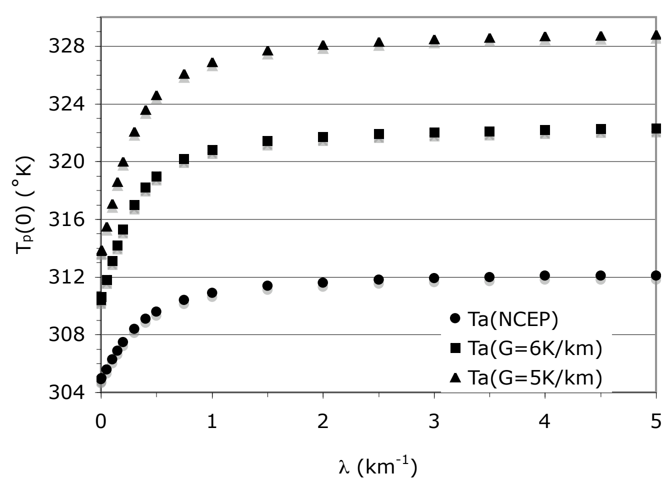
MISR Nadir **275 m** Image



MODIS Image + **Fire Power**



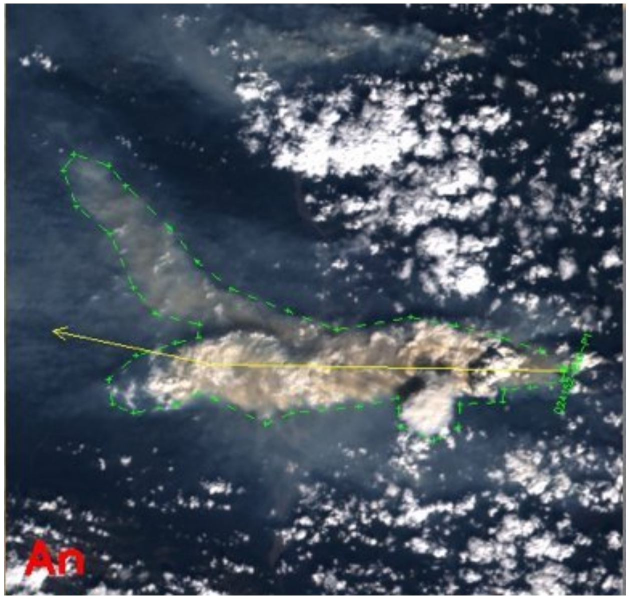
MISR **Plume Heights** for Sub-patches

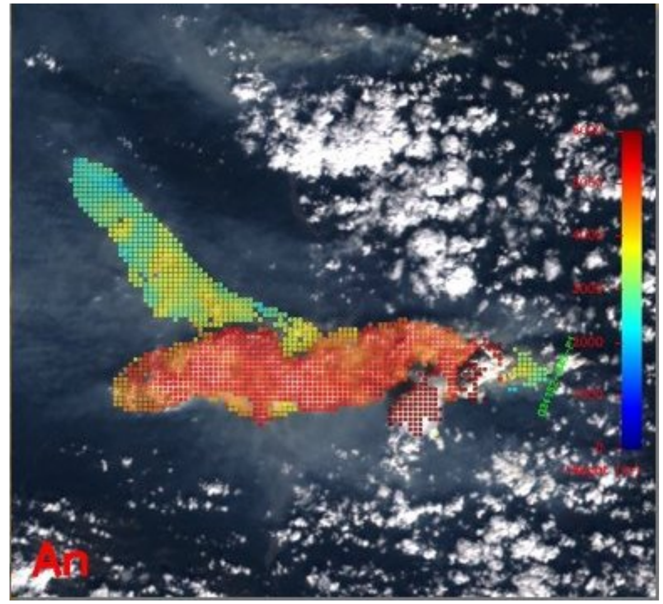


Very Simple Plume Parcel Model

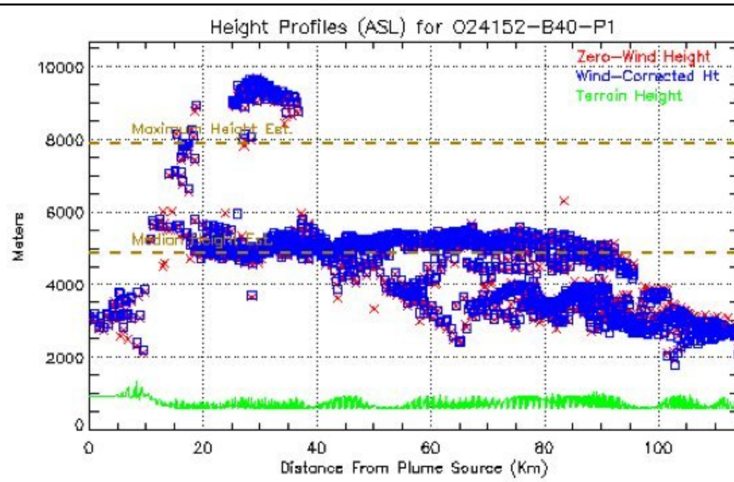
→ ***Broad swath + high spatial resolution*** needed to characterize sources

Wildfire Smoke Plume Database





http://www-misr2.jpl.nasa.gov/EPA-Plumes/



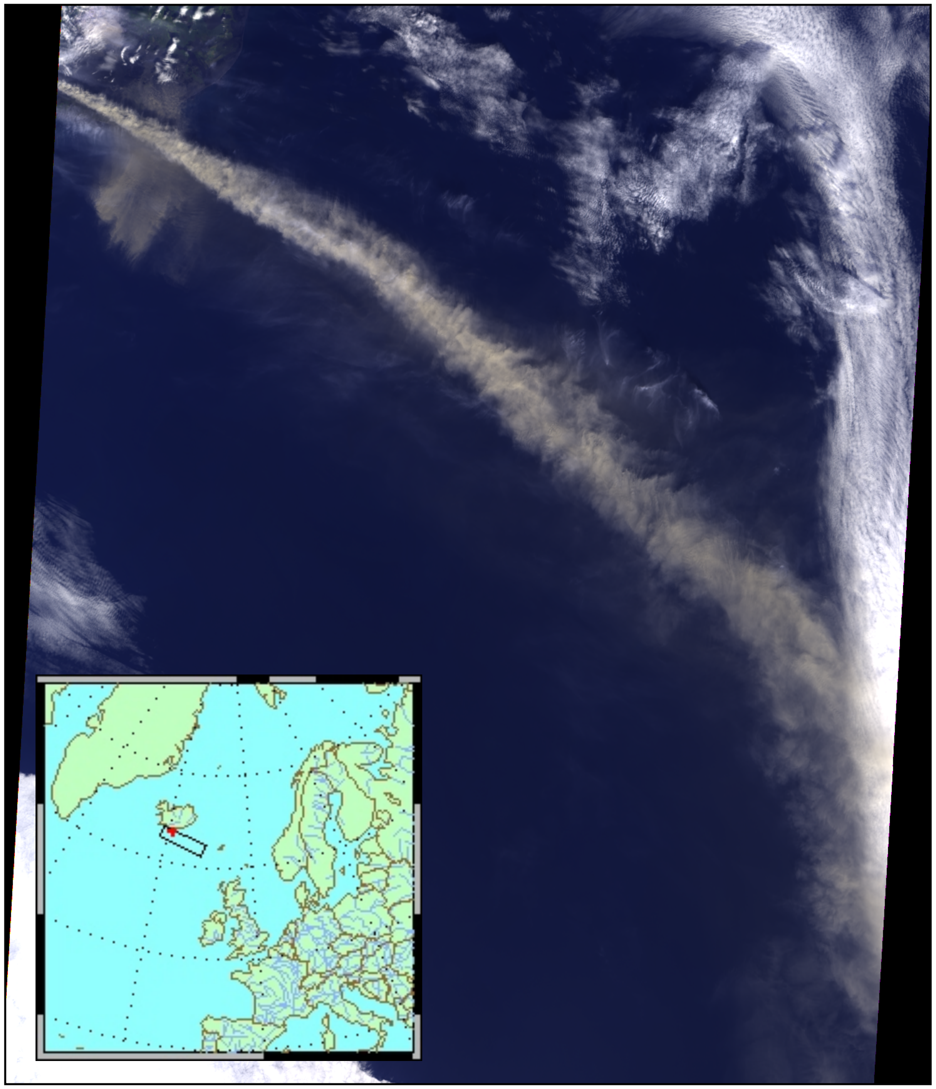
N. America
2002, 2004-2007

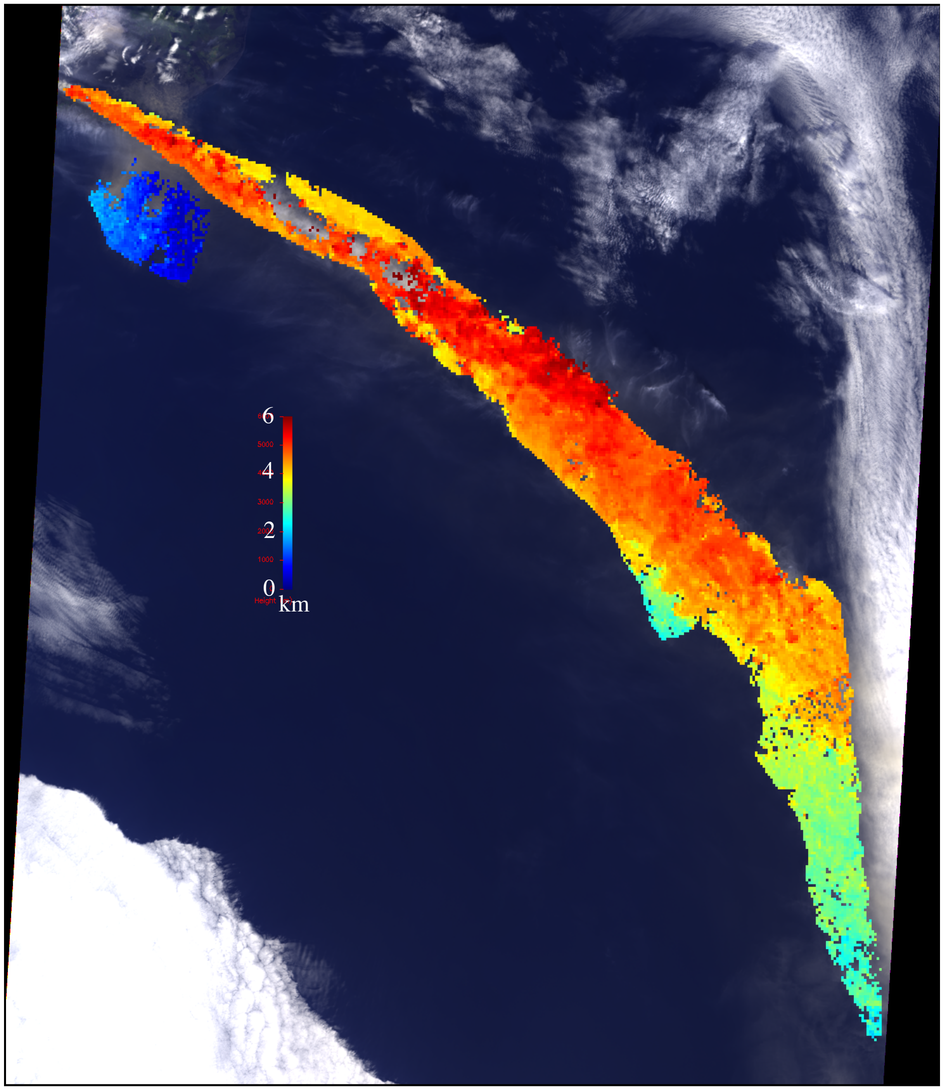
Africa
2005, 2006

D. Nelson, et al., Remt. Sens. 2013

MISR Stereo-Derived Plume Heights

07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39

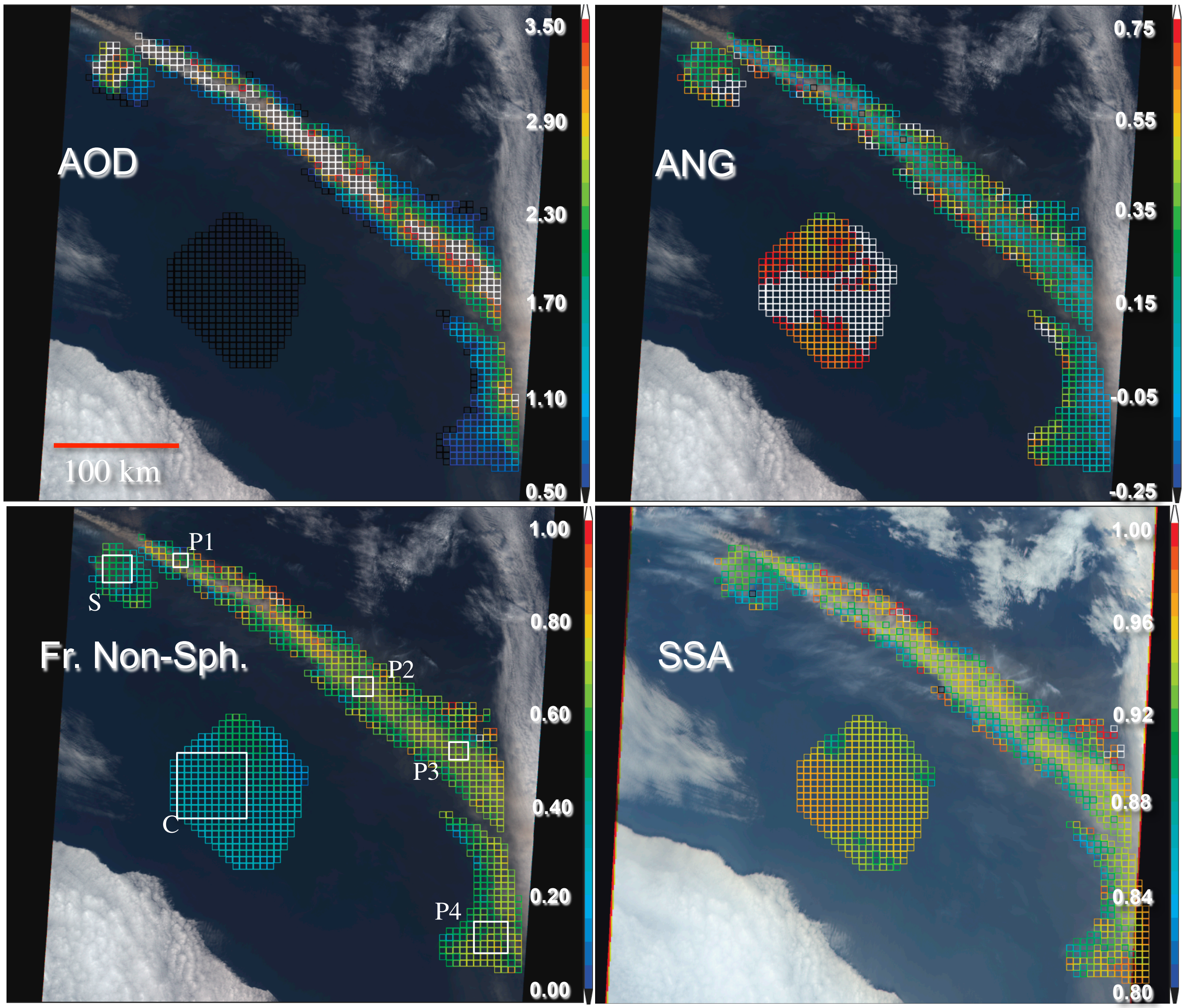




D. Nelson and the MISR Team, JPL and GSFC

MISR Research Aerosol Retrievals

07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39



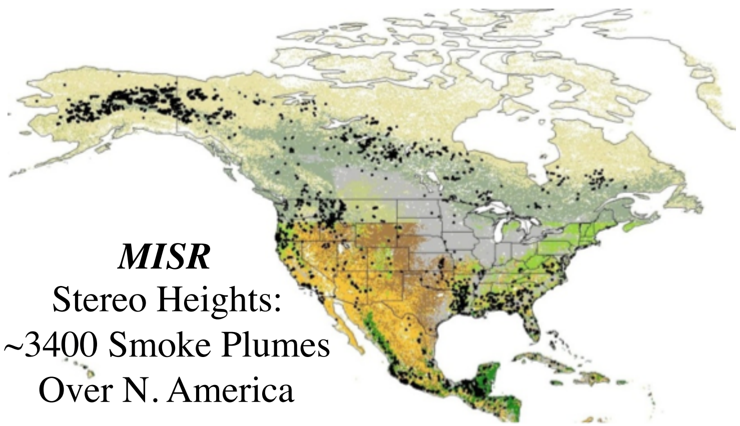
Plume Particles

- Distinct from background
  - -- ***larger***, ***darker***
  - -- ***much higher AOD***
- ***Non-spherical*** dominated
- Brighten downwind
- Tend to decrease in size downwind

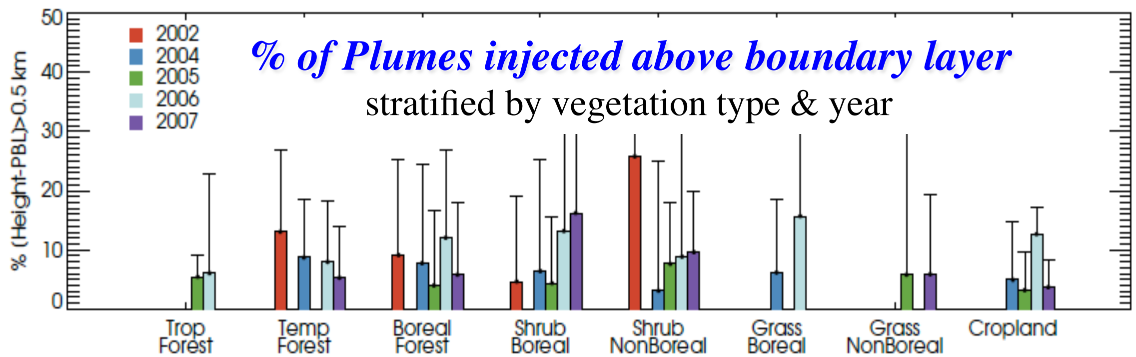
Kahn & Limbacher, ACP 2012

Wildfire Smoke *Injection Heights* & *Source Strengths*

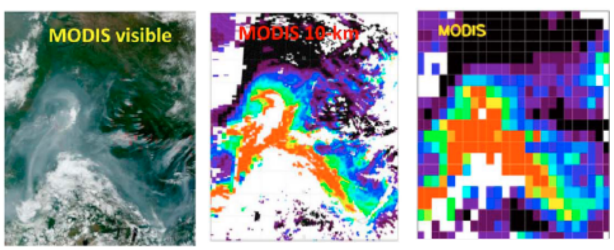
[These are *the two key parameters* representing aerosol sources in climate models]



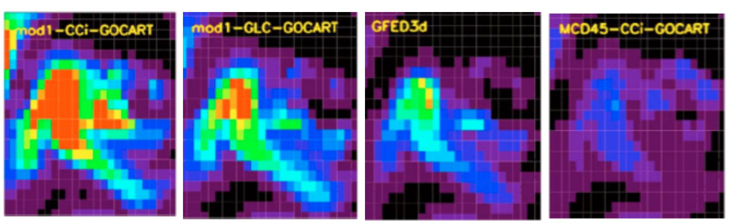
MISR
Stereo Heights:
~3400 Smoke Plumes
Over N. America



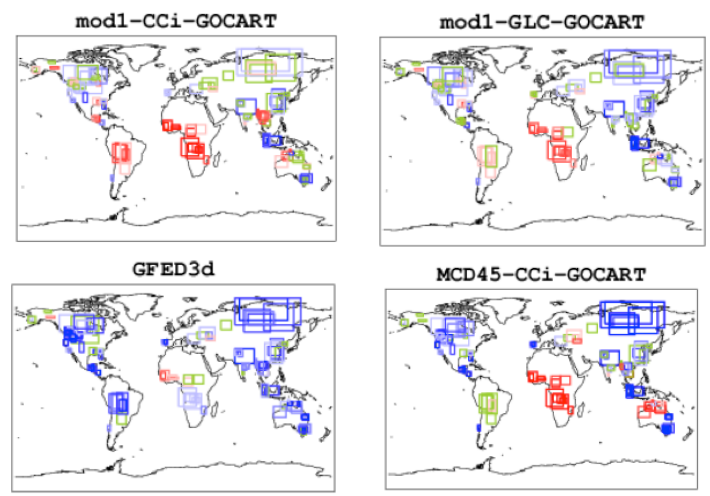
Val Martin et al. ACP 2010



MODIS Smoke Plume Image & Aerosol Amount Snapshots



GoCART Model-Simulated Aerosol Amount Snapshots
for *Different Assumed Source Strengths*

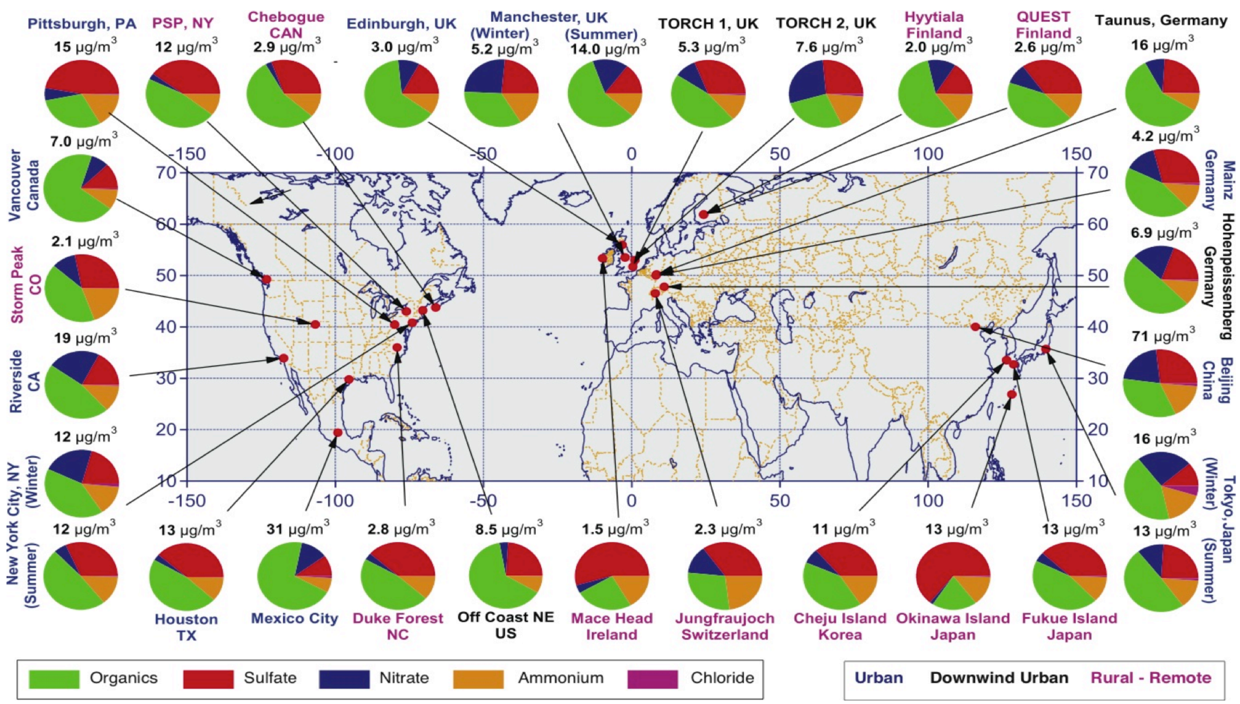


Different Techniques for *Assuming Model Source Strength*
Overestimate or ***Underestimate*** Observation
Systematically in Different Regions

Petrenko et al., JGR 2012

Applications – Air Quality

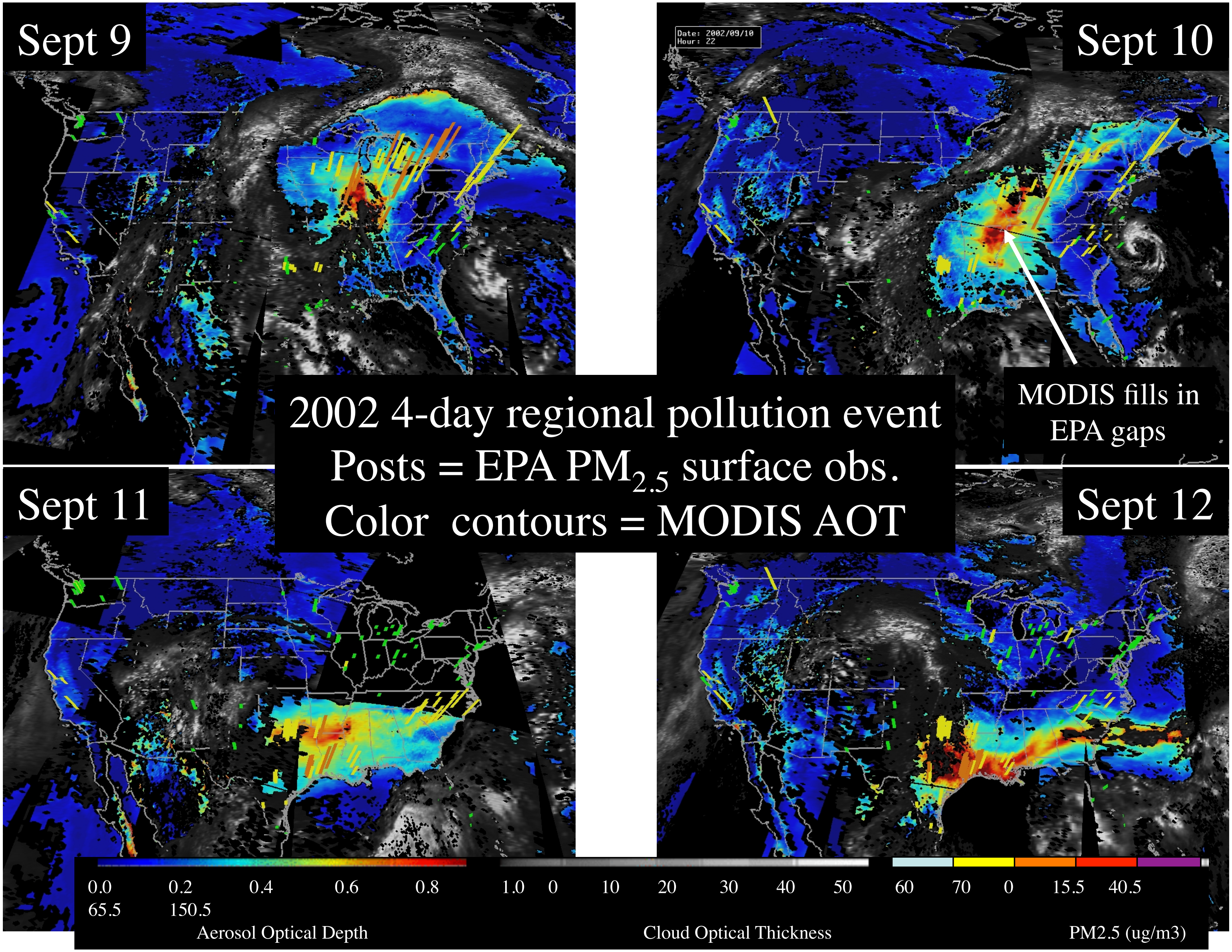
Regional-scale **Air Quality** Assessment



Zhang et al., GRL. 2007

Surface-based mass-spec aerosol composition measurements

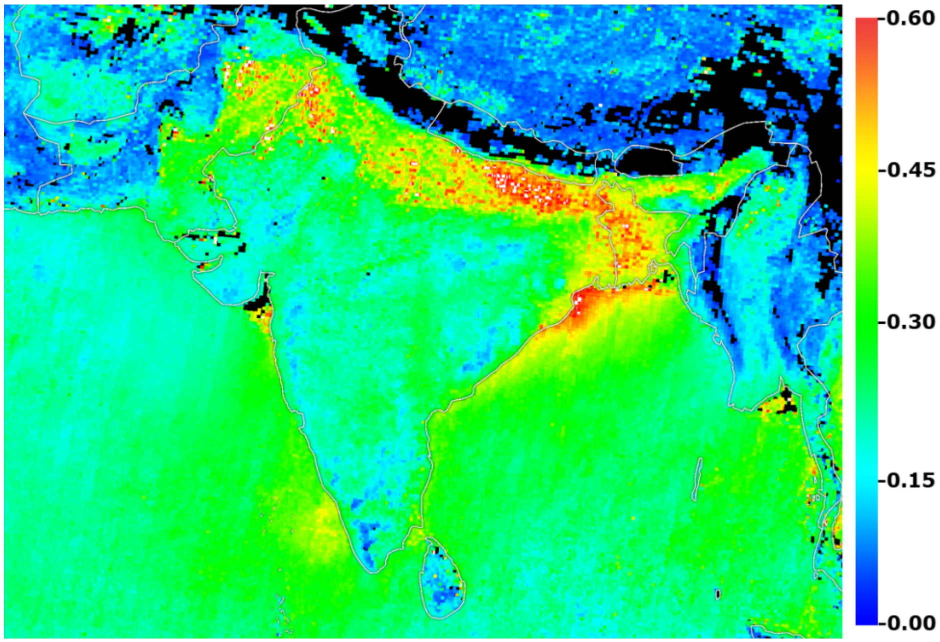
- **Need to isolate *Near-surface Aerosol Component***
- **Need sufficient *Spatial-Temporal Coverage* to capture *Severe Events***
- **Detailed *Chemical Speciation* often required**
- ***High Spatial Resolution* often required** (e.g., in Urban areas)

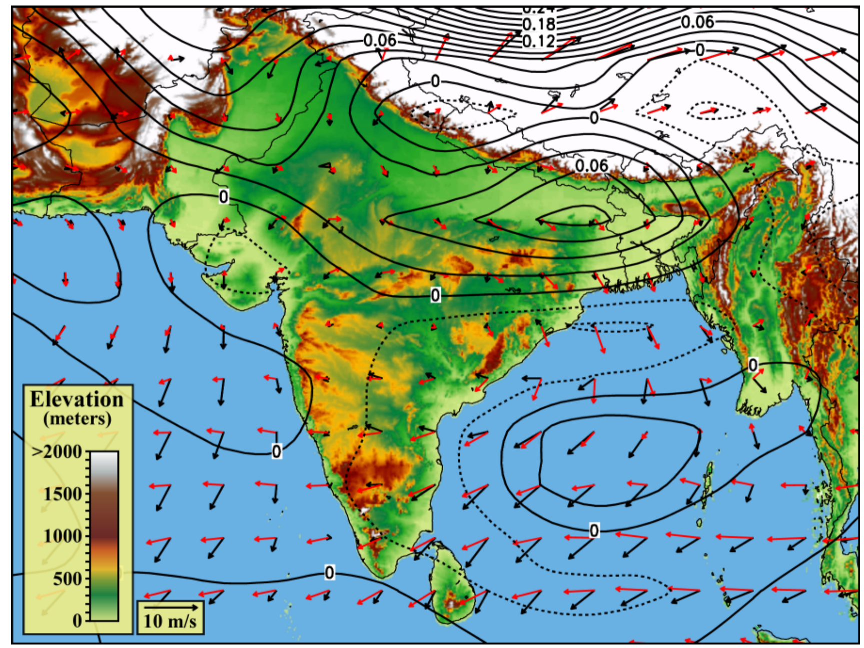


http://www.star.nesdis.noaa.gov/smcd/spb/aq/

From: MODIS Team/IDEAS Group

Pollution Aerosol Concentrated in Ganges Valley near Kanpur, India (MISR)





MISR mid-visible AOD

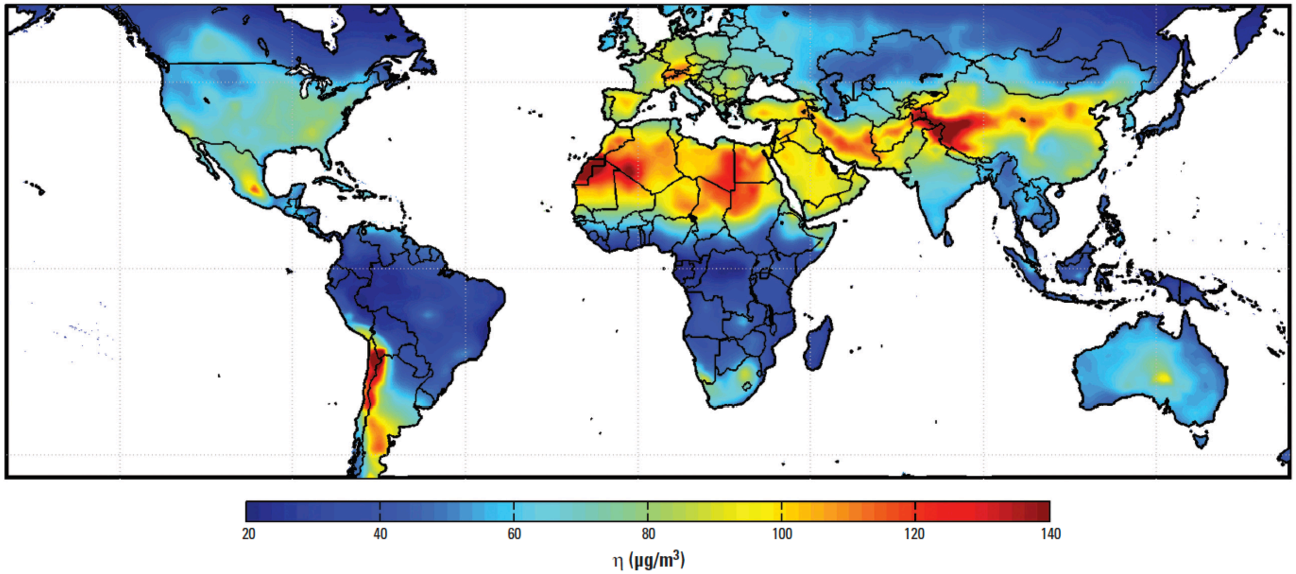
[**Winter**, 2001-2004; white --> AOD >0.6]

NCEP Winds + Topography

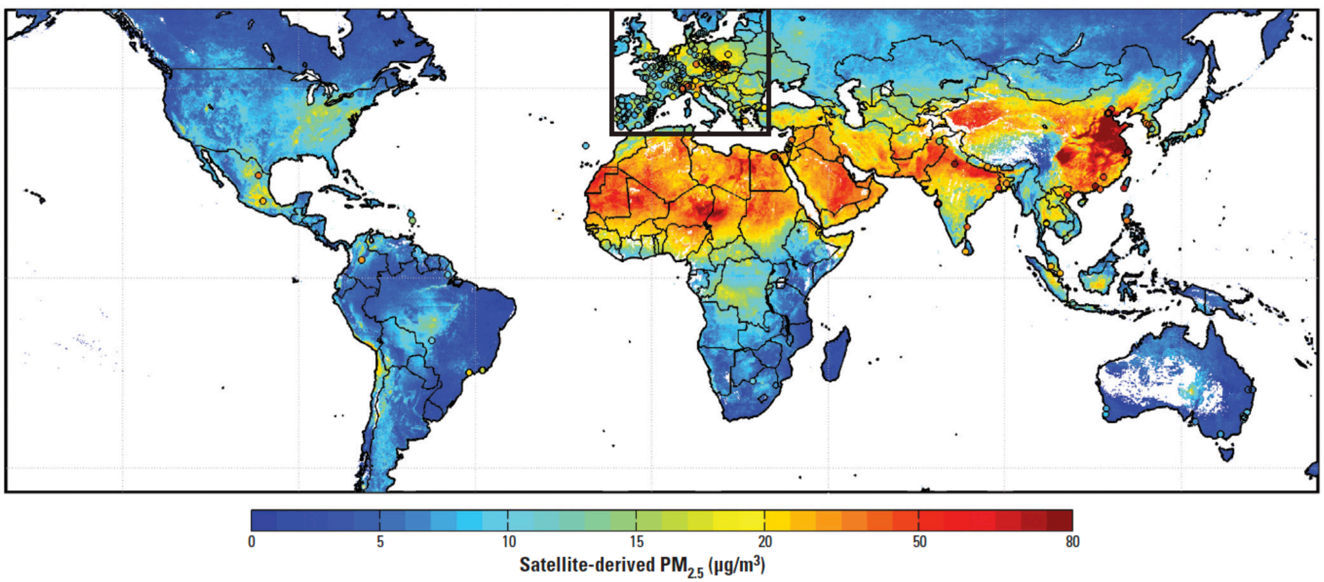
[Black=surface; Red=850 mb; contours=vertical, solid=subsidence]

Di Girolamo et al., GRL, 2004

Air Quality: BL Aerosol Concentration
[MISR + MODIS] AOD & GEOS-Chem Vertical Distribution



[BL $PM_{2.5}$] / [Total-col. AOD]
2001- 2006



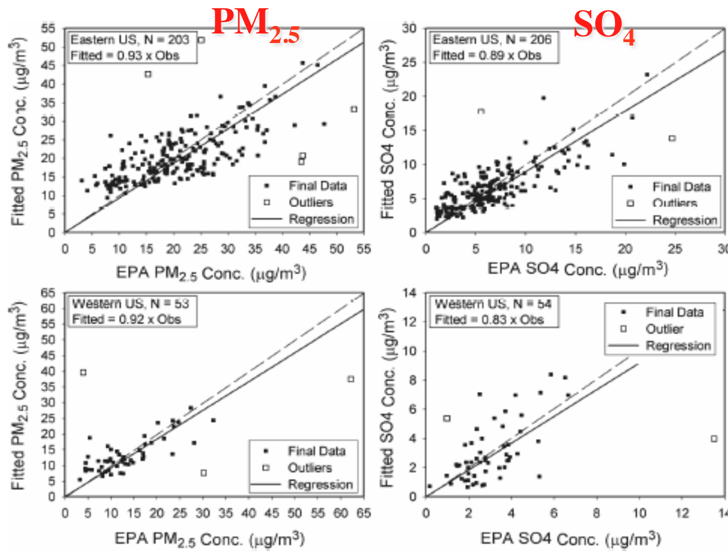
Derived $PM_{2.5}$

Van Donkelaar et al., Environ. Health Prespect. 2010

MISR - GEOS-Chem Regression Model To Map **Near-surface Aerosol Pollution**

***MISR*-Constrained Model**

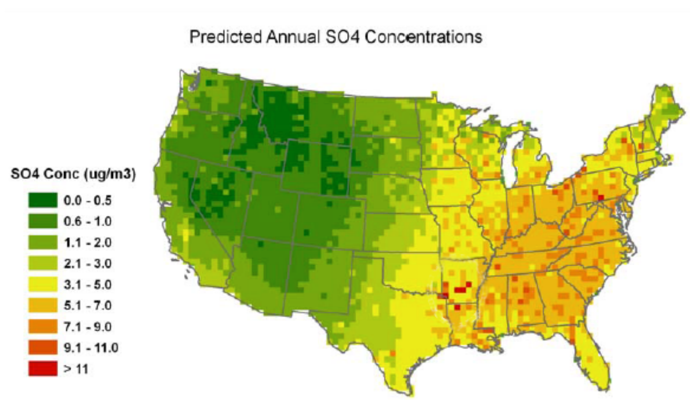
$PM_{2.5}$ **SO_4**



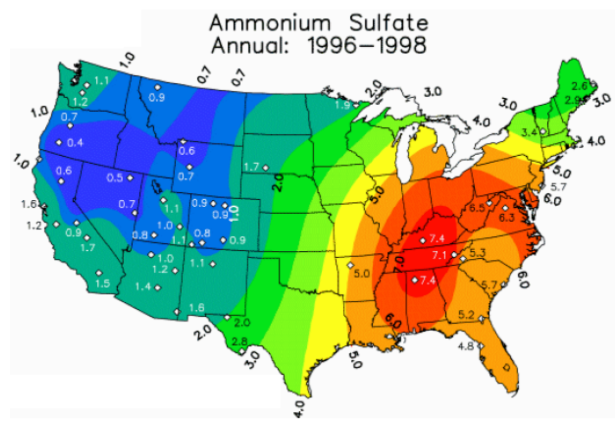
Eastern US

Western US

EPA *Surface* Measurements



MISR / GEOS-CHEM ***Retrieval***

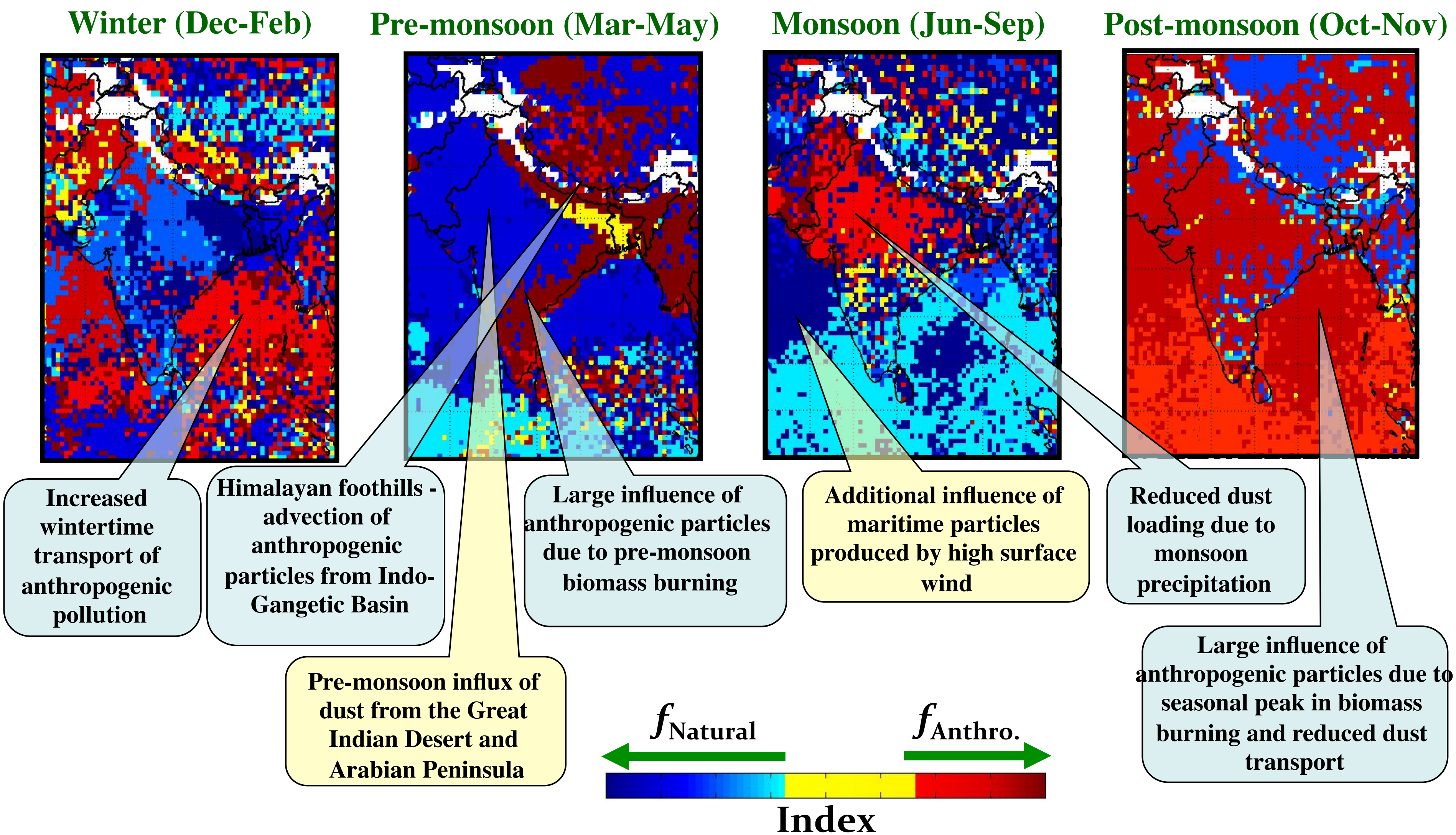


Surface network (IMPROVE) measurements

- Using MISR ***Particle Shape*** as well as AOT to constrain model --> much better result
- Can add column ***Size*** and ***SSA*** information when MISR retrieval is more robust

Y. Liu et al, JAWMA 2007

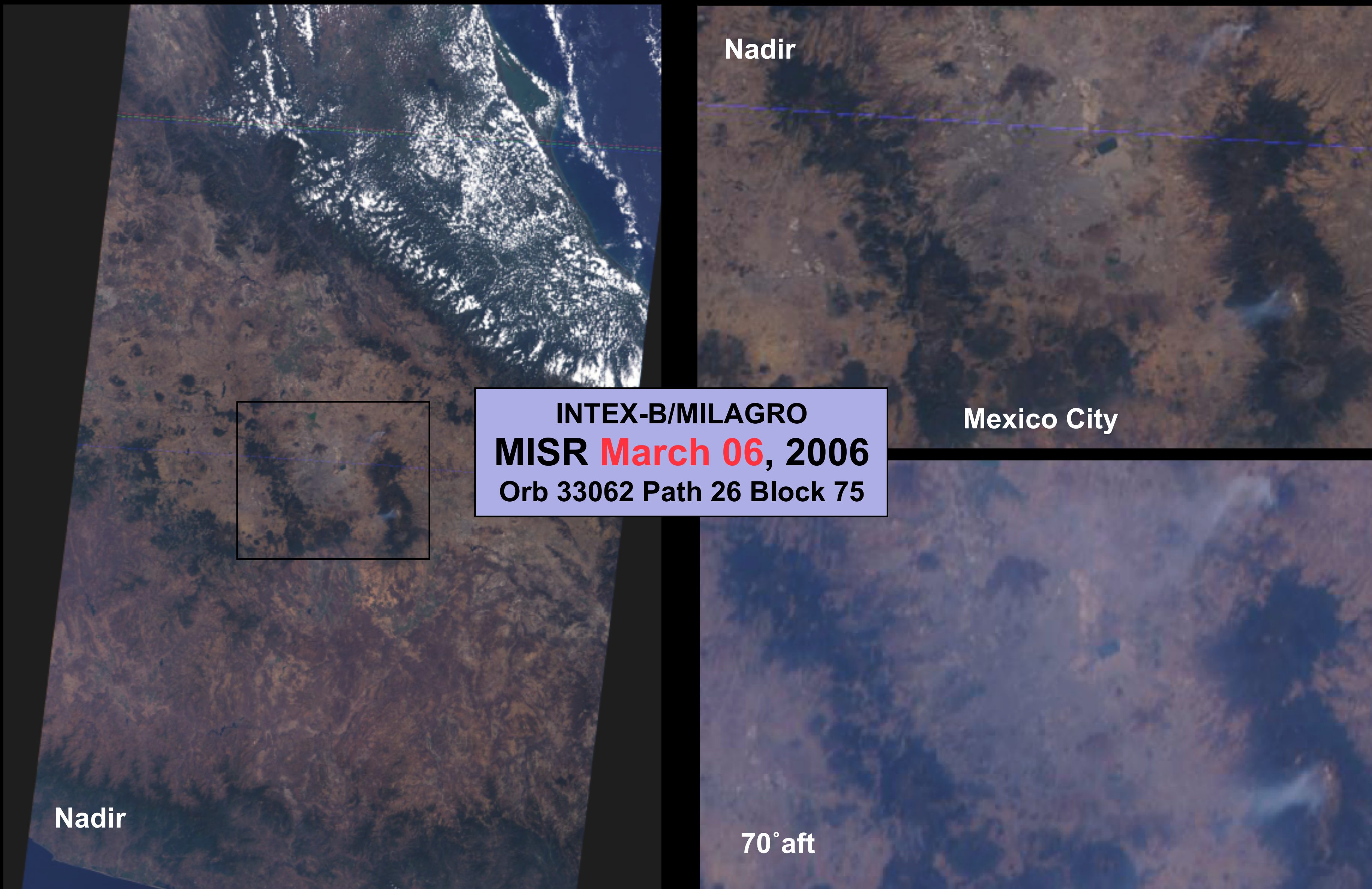
Characterizing seasonal changes in anthropogenic and natural aerosols w.r.t. preceding season over the Indian Subcontinent



Index uses MISR-retrieved particle shape and size constraints to separate natural from anthorpogenic aerosol

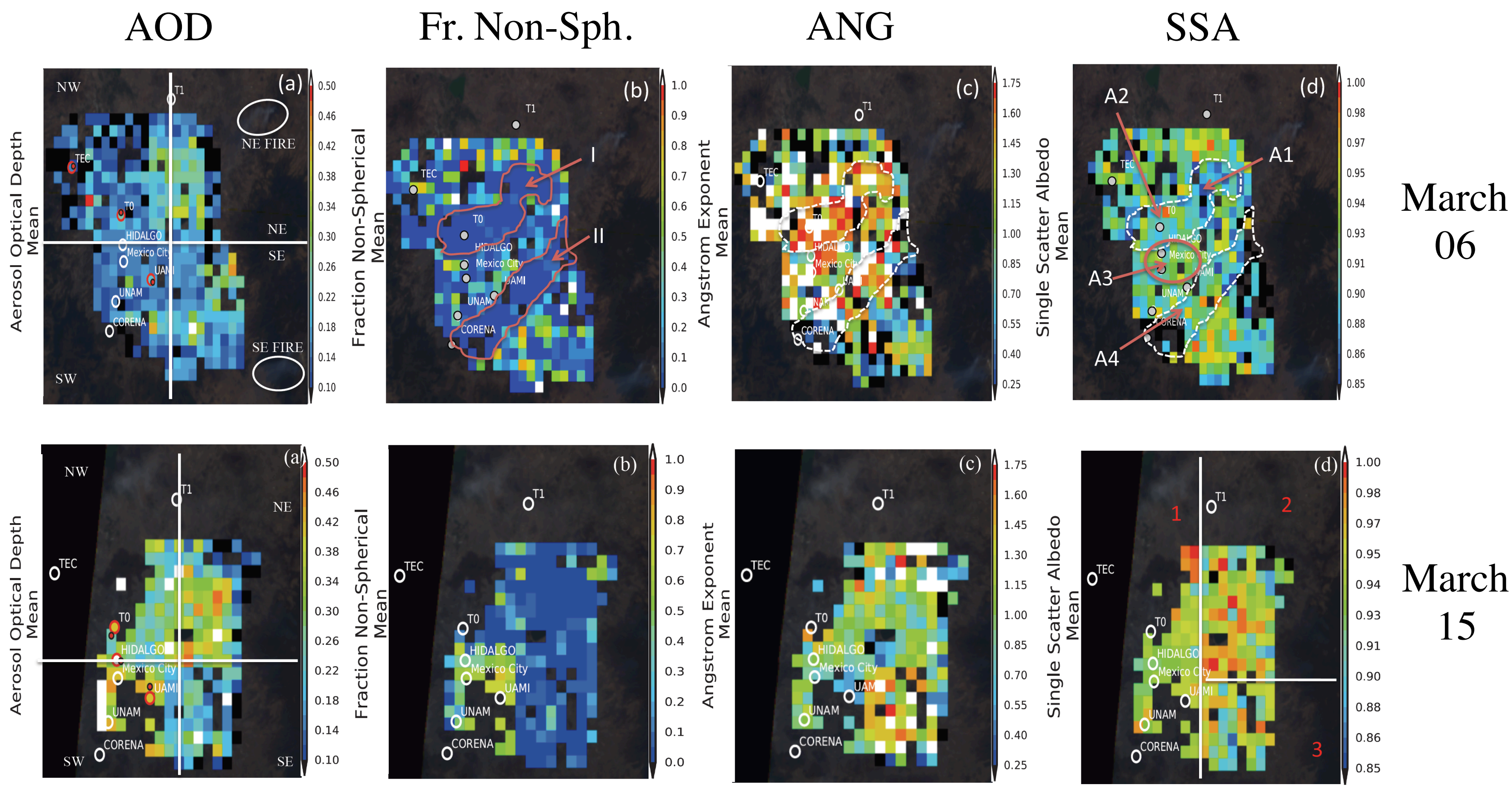
Dey & Di Girolamo **JGR 2010**

Mapping AOD & Aerosol Air-Mass-Type in Urban Regions



Patadia et al.

Urban Pollution AOD & Aerosol Air Mass Type Mapping
INTEX-B, 06 & 15 March 2006

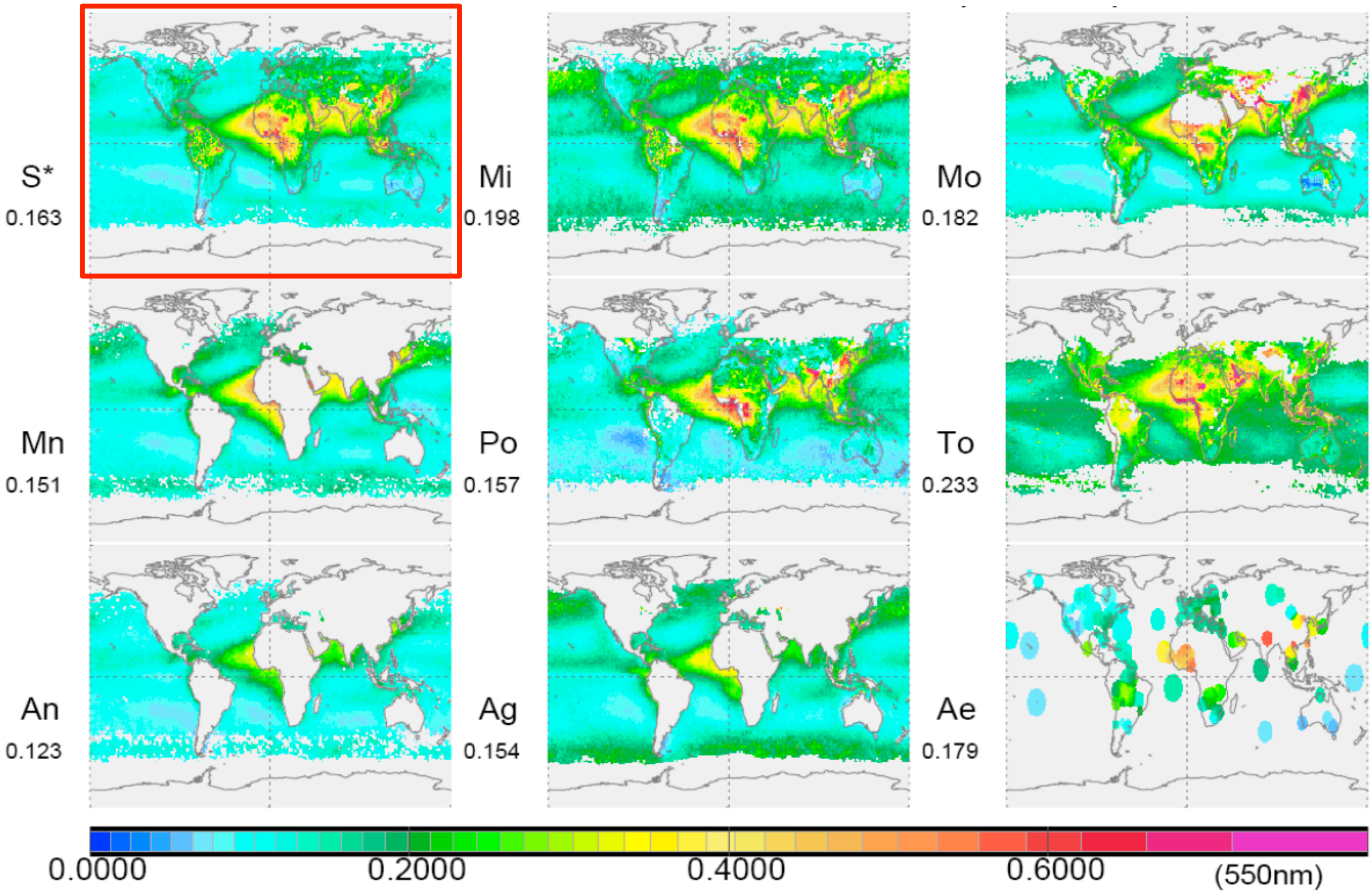


Aerosol Air Masses: ***Dust*** (non-spherical), ***Smoke*** (spherical, spectrally steep absorbing), and ***Pollution*** particles (spherical, spectrally flat absorbing) dominate specific regions

Patadia et al., ACP 2013

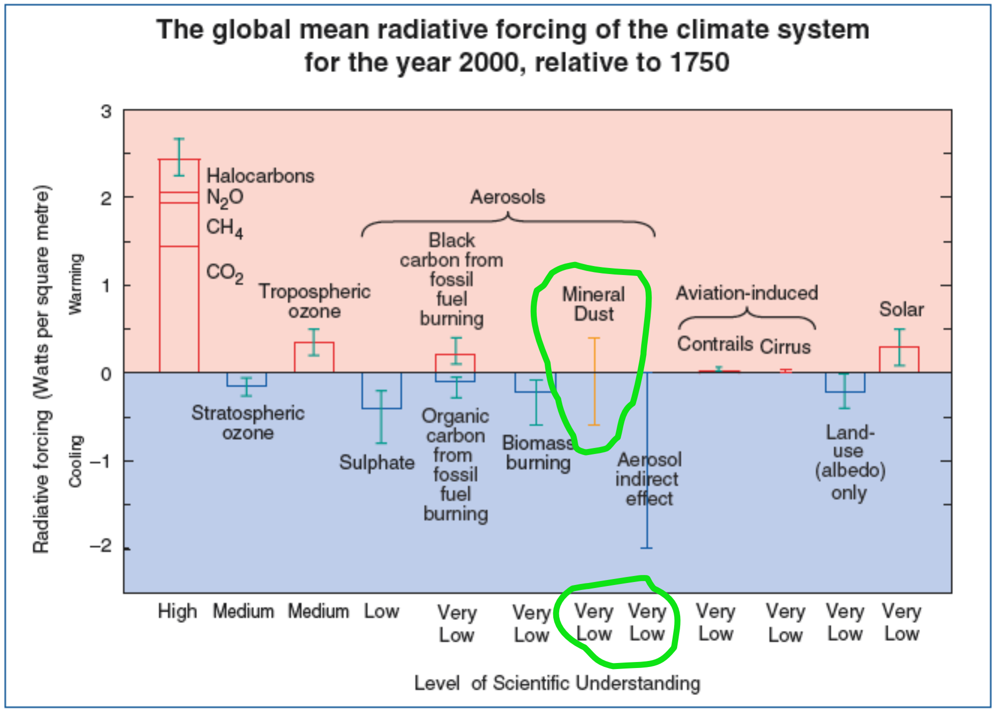
Applications –
Aerosol Climate Forcing

Multi-year Annual Average ***Aerosol Optical Depth*** from Different Measurements + ***Synthesis*** (S^*)



From: *Kinne et al. ACP 2006*

Even DARF and Anthropogenic DARF are *NOT* Solved Problems (Yet)



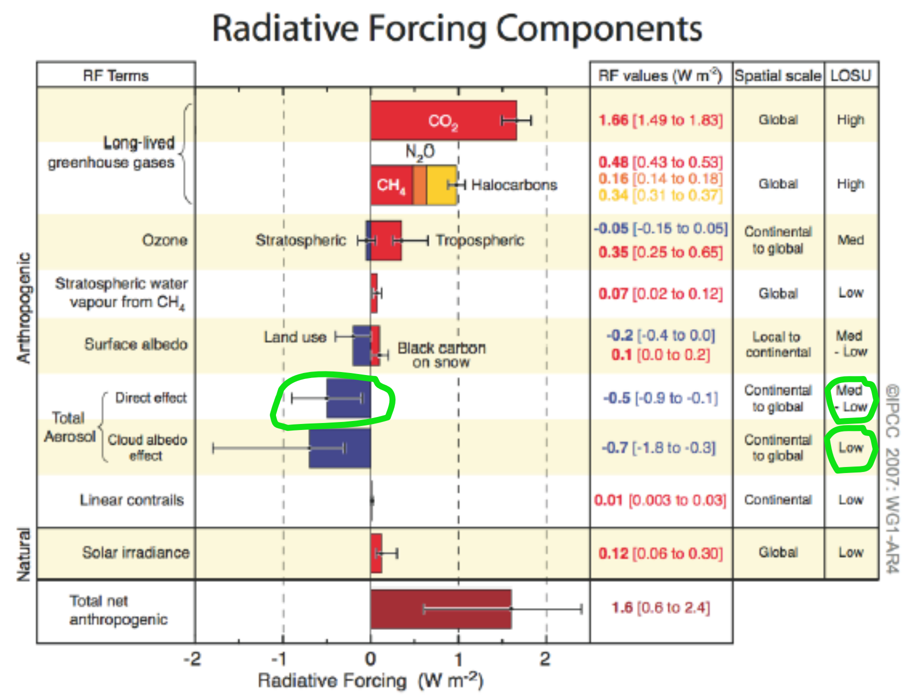
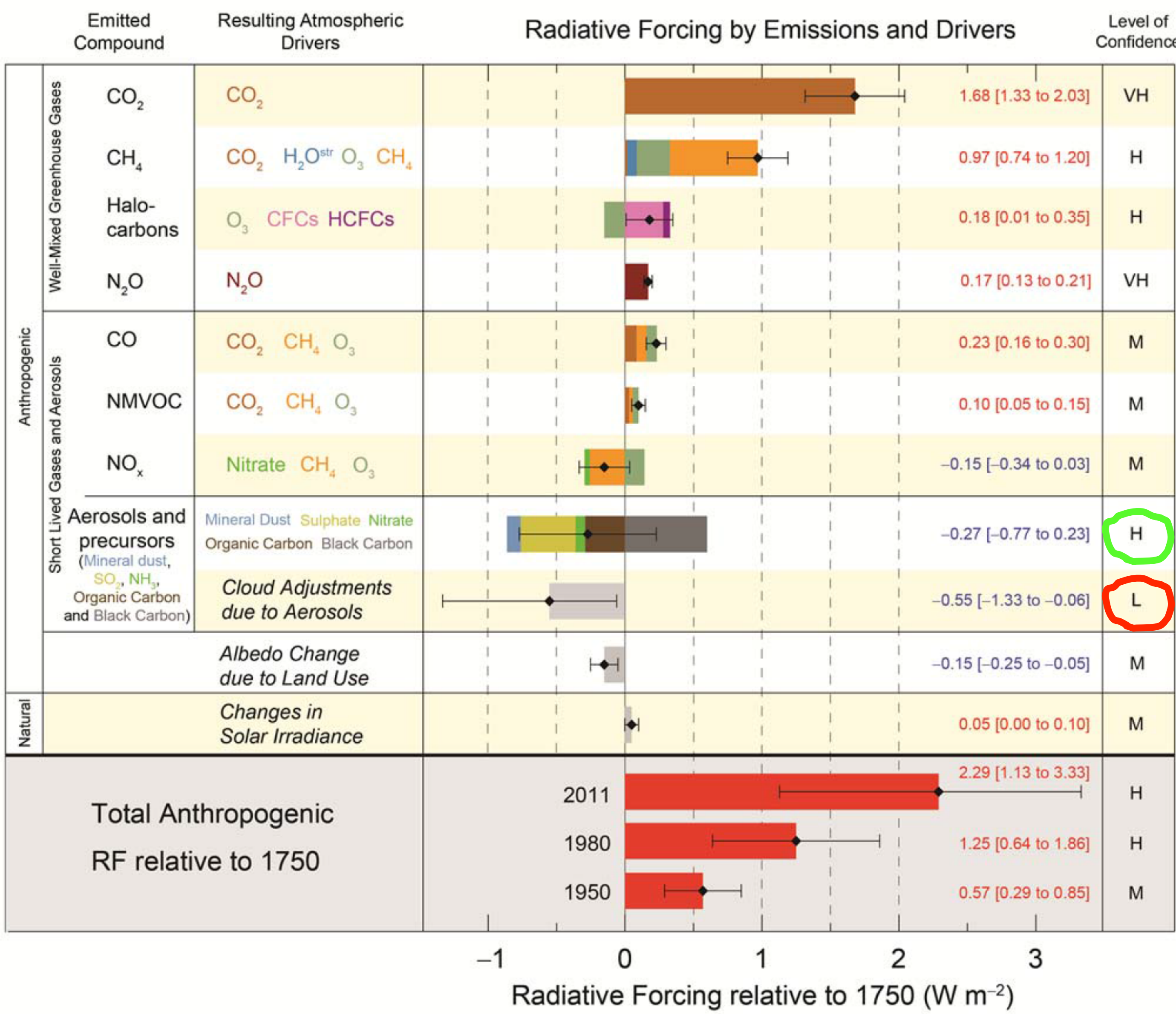


FIGURE SPM-2. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. Range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}

IPCC AR3, 2001
(Pre-EOS)

IPCC AR4, 2007
(EOS + ~ 6 years)

The *Current* Assessment of Climate Forcing Factors

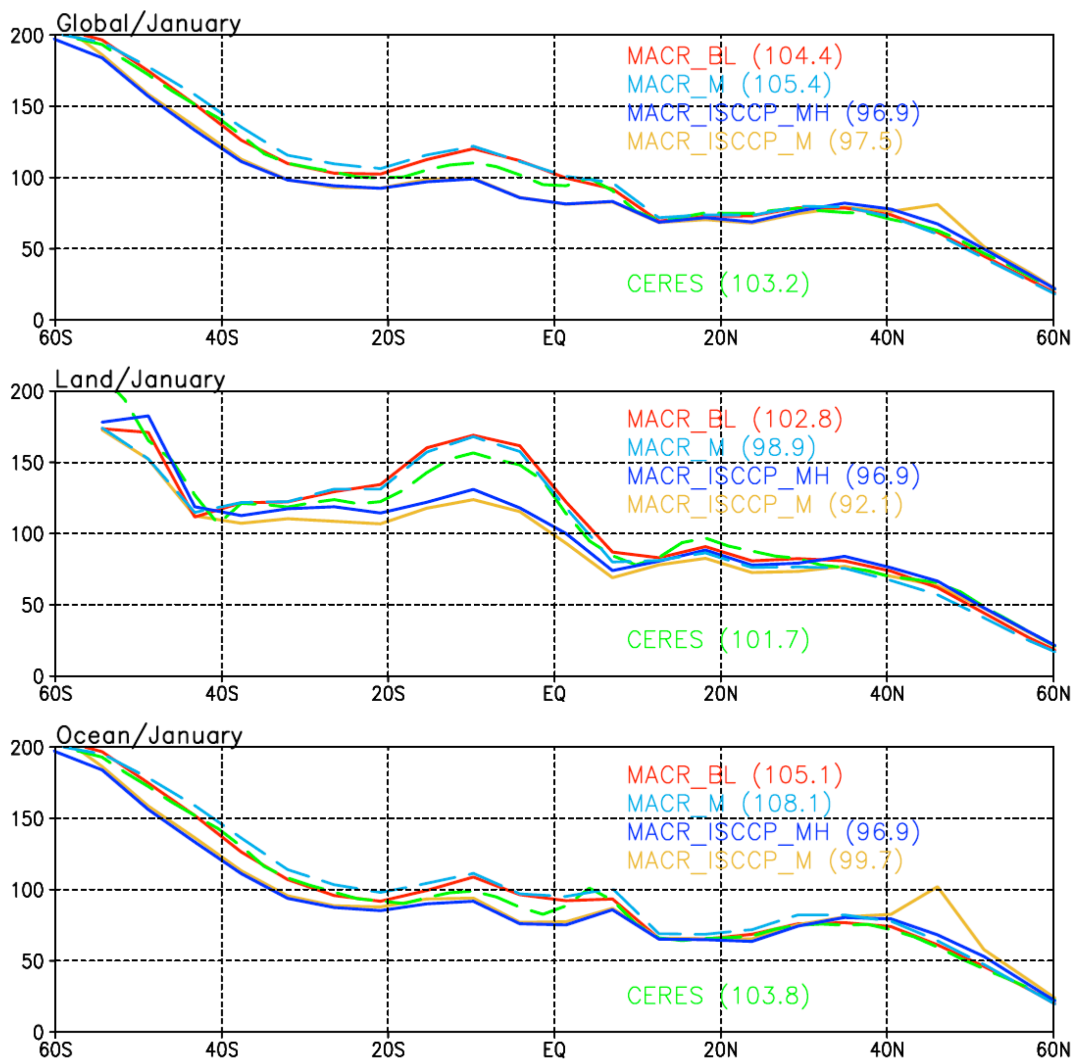


Global average, & compared to other uncertainties in the models – ***What about aerosol type?!***

The next big area to address

IPCC ***AR5*** *2013*

Measurement Synthesis: Aerosol Short-wave Direct Radiative Forcing

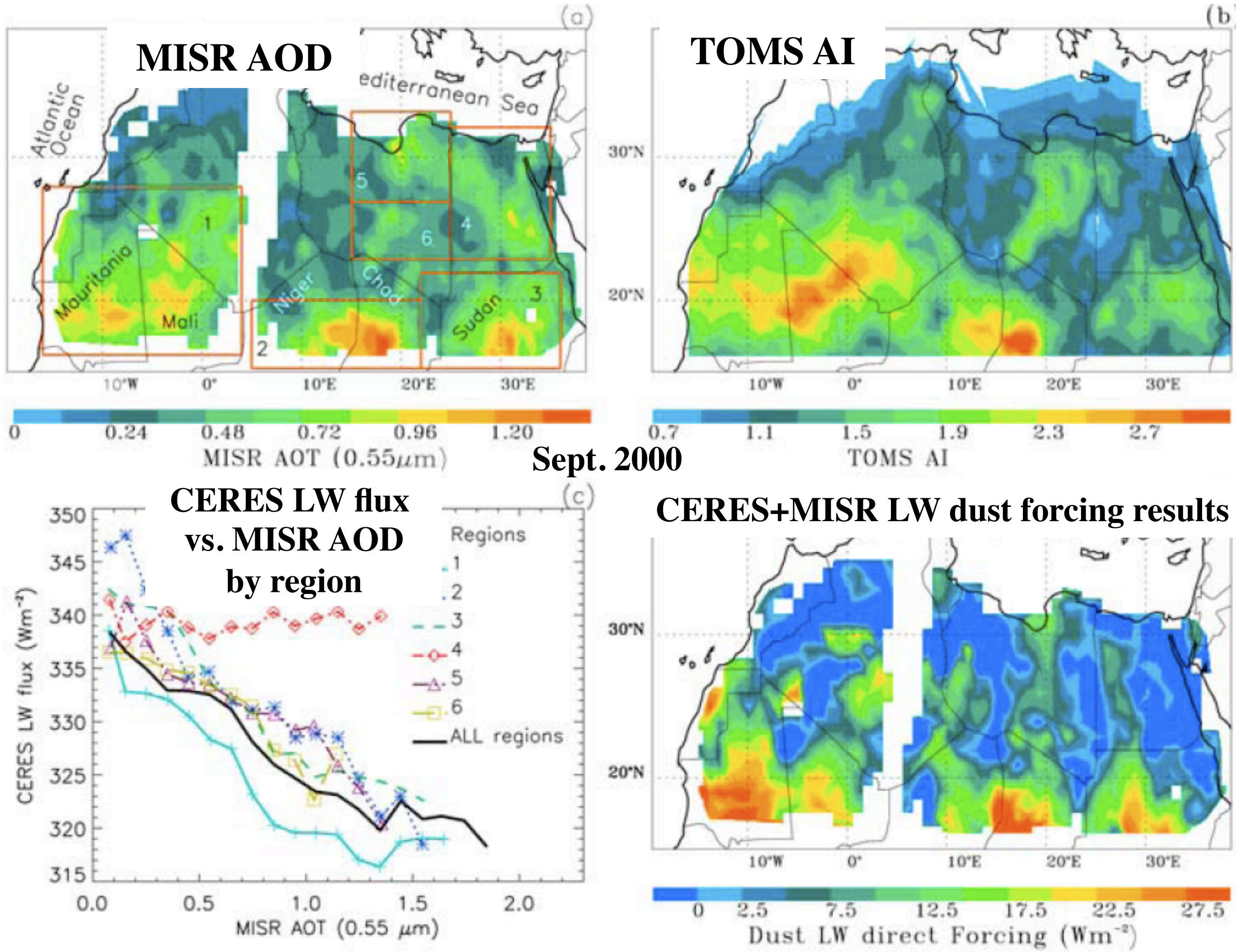


Outgoing zonal TOA fluxes calculated with Monte-Carlo Aerosol-Cloud-Radiation model constrained with ***MISR AOD***, ***AERONET*** particle properties, ***GOCART*** interpolation, and using ***four choices of cloud data*** from ISCCP and CERES (hourly monthly and monthly mean).

Results are ***compared to CERES*** and validated using BSRN.

*"Overall, such agreements suggest that global data sets of aerosols and cloud parameters released by recent satellite experiments (MISR, MODIS and CERES) **meet the required accuracy to use them as input to simulate the radiative fluxes** within instrumental errors." -- Kim & Ramanathan JGR 2008*

Aerosol Long-wave Radiative Forcing Over Desert



Terra/ ***MODIS*** – 1 km resolution cloud-clearing for 30 km CERES footprint

MISR – AOD over bright desert surface

CERES – TOA LW flux as a function of MISR AOD [~15±5 W/(m^2 – AOD)]

Region 4 – Dust is near-surface [***TOMS*** does not see it; LW flux indep. of AOD]

Result depends on dust vertical distribution & H_2O_v

Zhang & Christopher GRL 2003

Over-Land Aerosol Short-wave Radiative Forcing w/Consistent Data

The slope of:

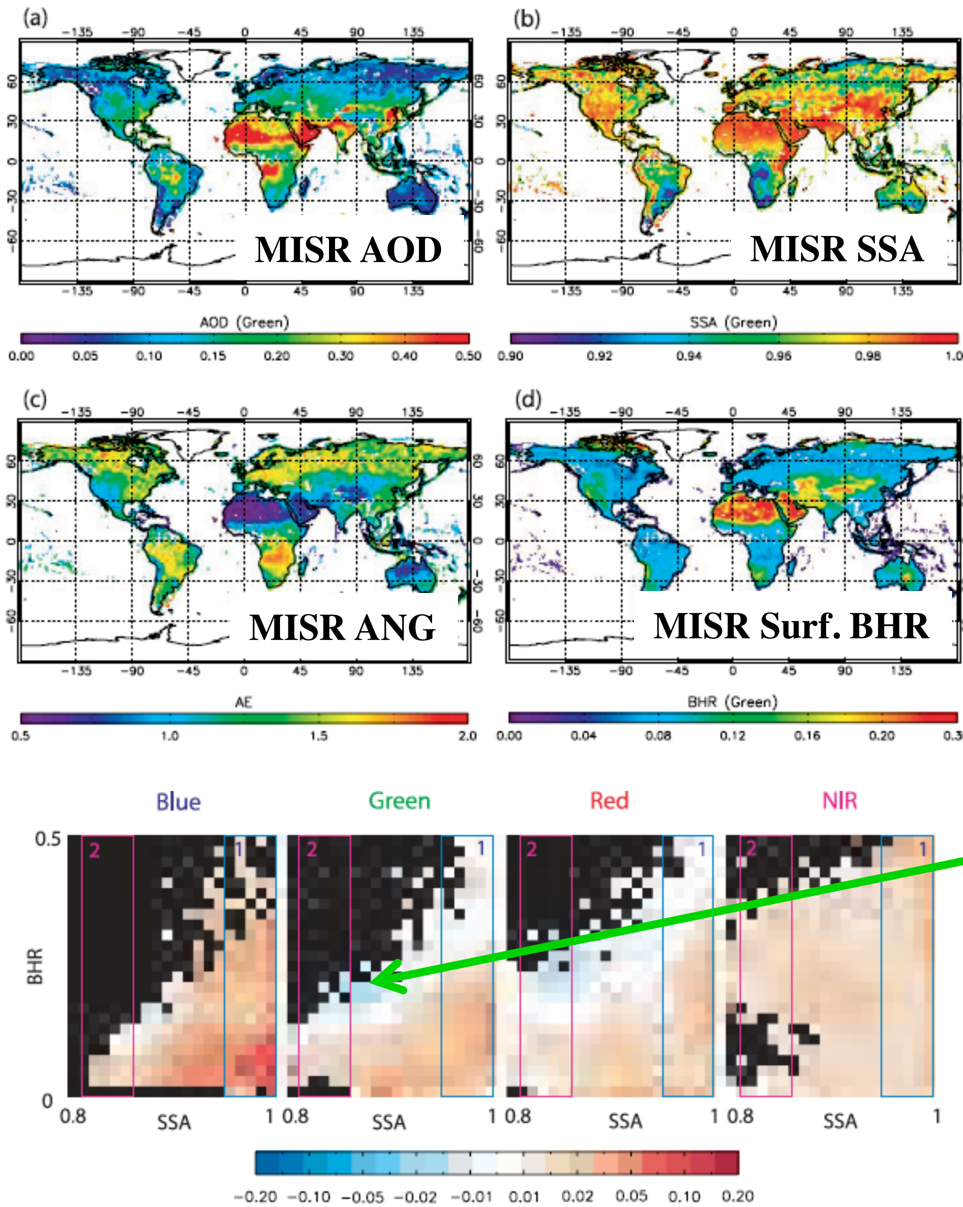
TOA albedo vs. AOD

For data stratified by:

Surface BHR

Produces:

Spectral aerosol radiative efficiency



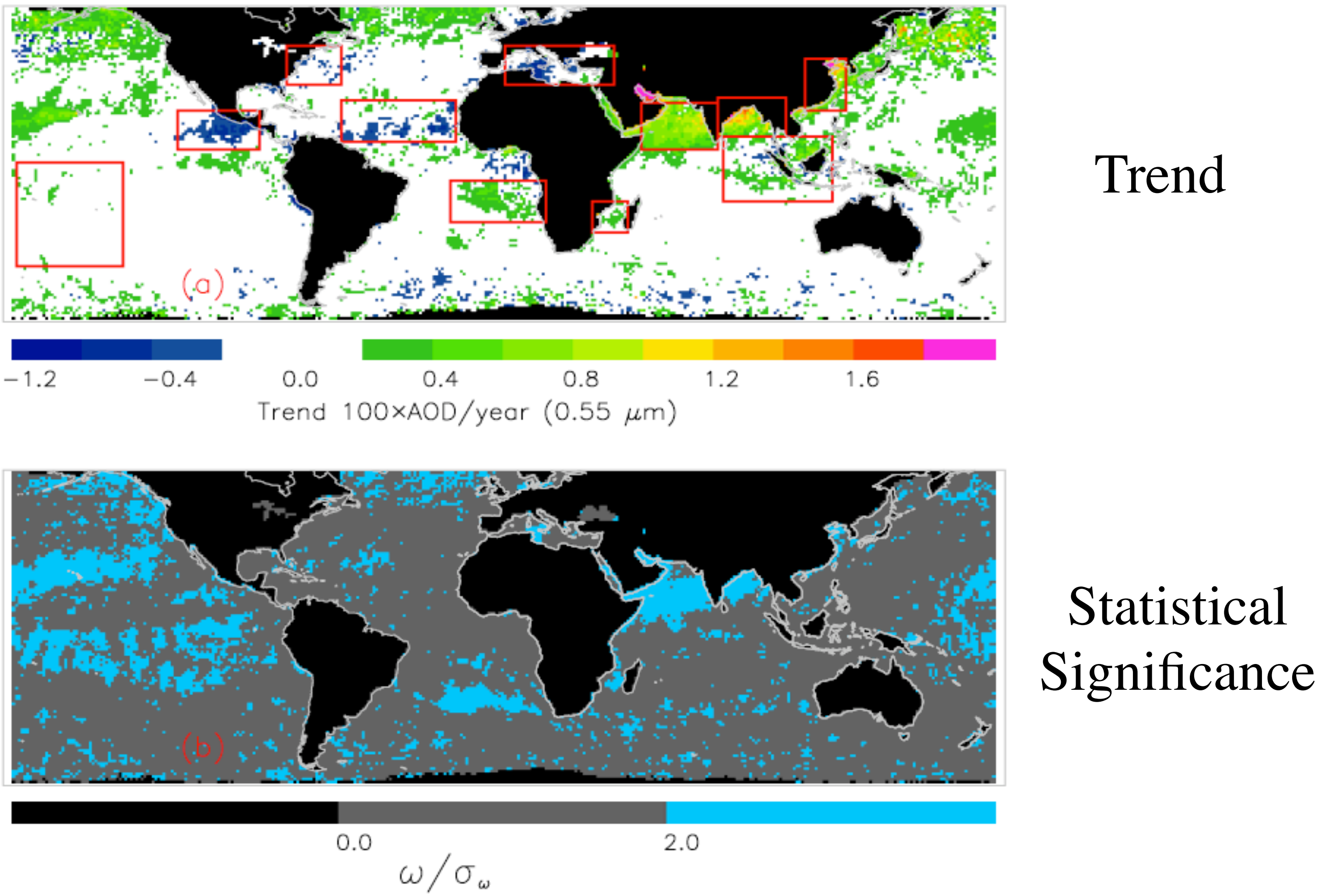
Bright surface
+ dark aerosol
= decreasing
albedo w/AOD

Y. Chen et al. JGR 2009

Applications –

Long-Term AOD Trends

MODIS10-Year Global/Regional Over-Water AOD Trends



- Statistically ***negligible*** *(±0.003/decade)* ***global-average*** over-water AOD trend
- Statistically ***significant increases*** over the Bay of Bengal, E. Asia coast, Arabian Sea

Zhang & Reid, ACP 2010

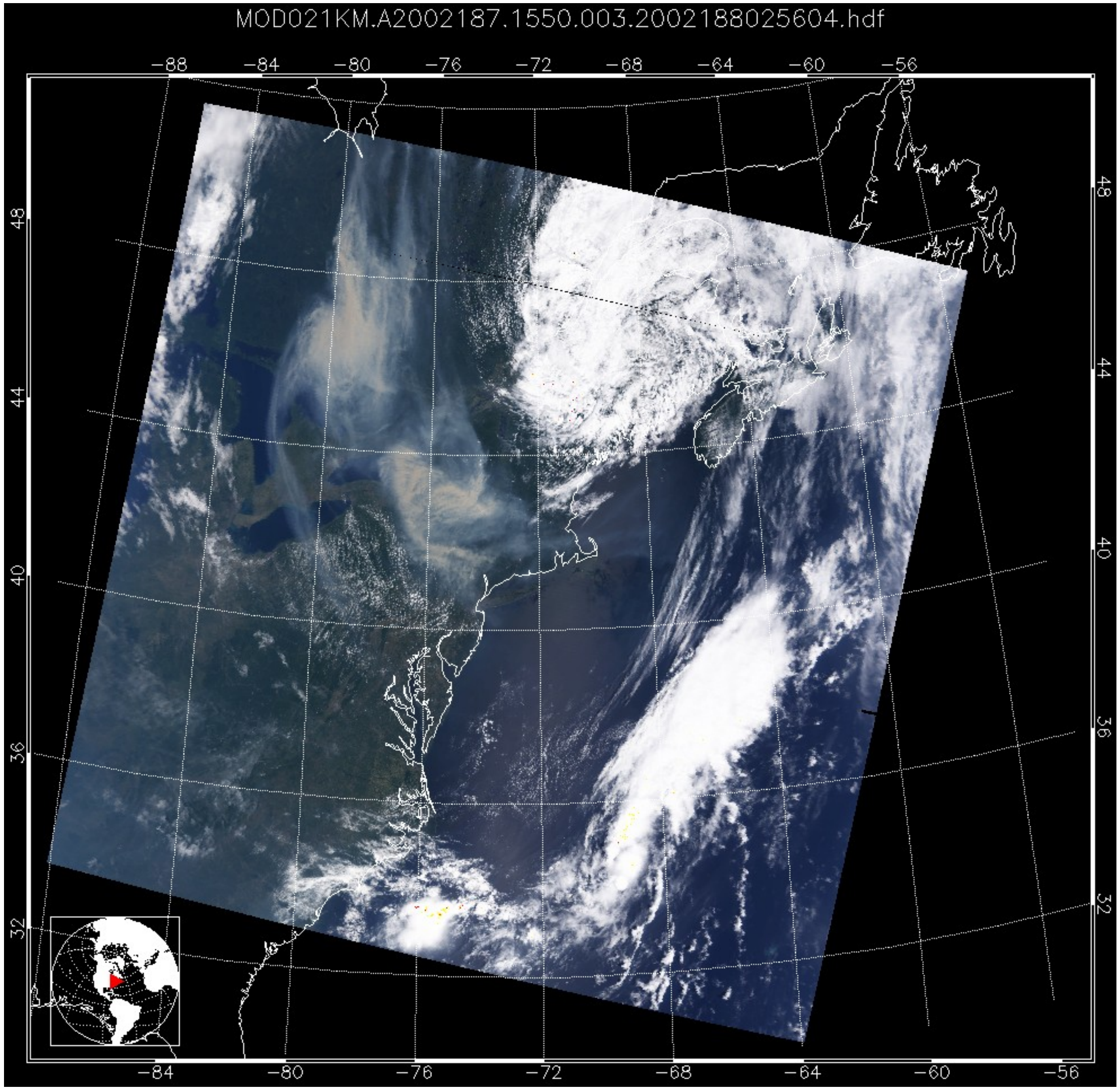
Using MSIR Products

Introduction to Aerosol Product Content

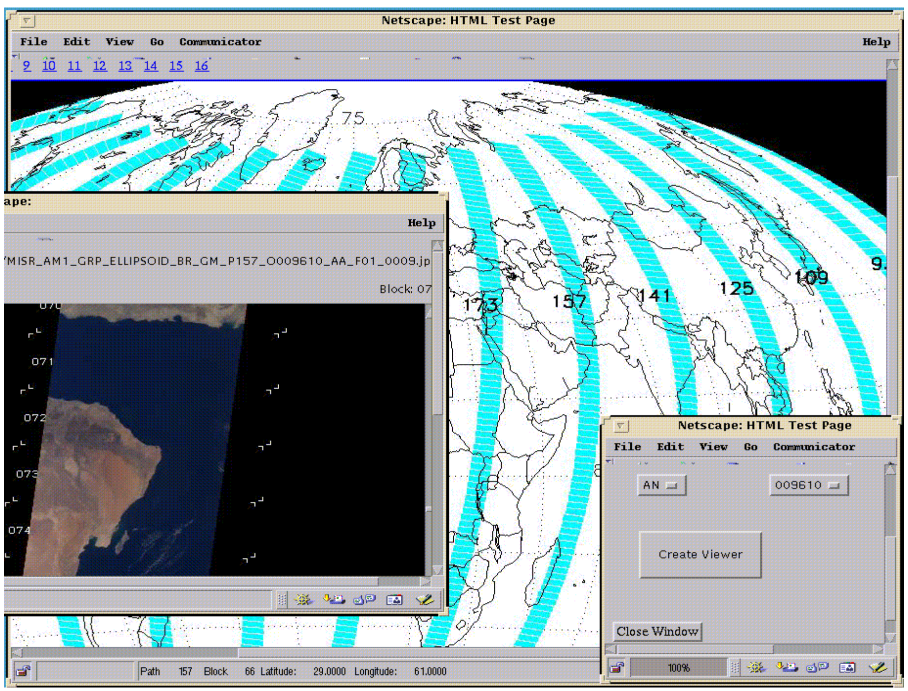
There is a vast amount of detail -- and documentation

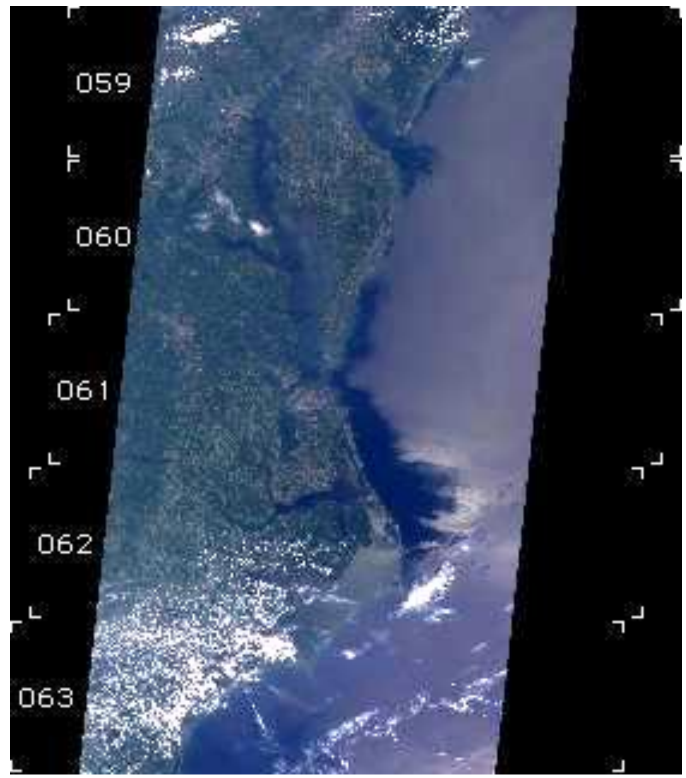
- **I'd aim to get a good overview of the capabilities**
- **Then learn what you need of the products & software**
- **The Data Archives (DAACs) are set up to help users**

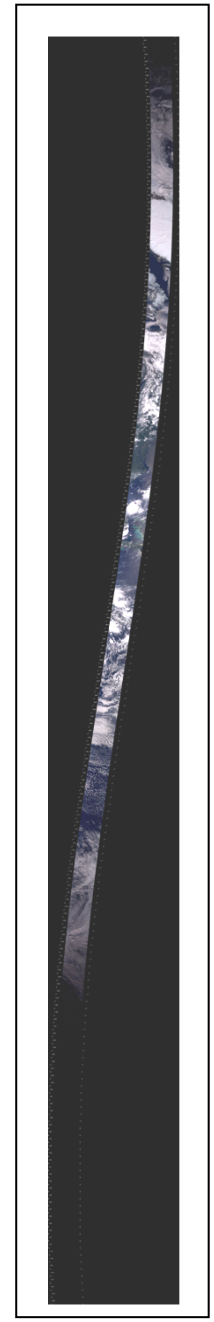
MODIS Granule



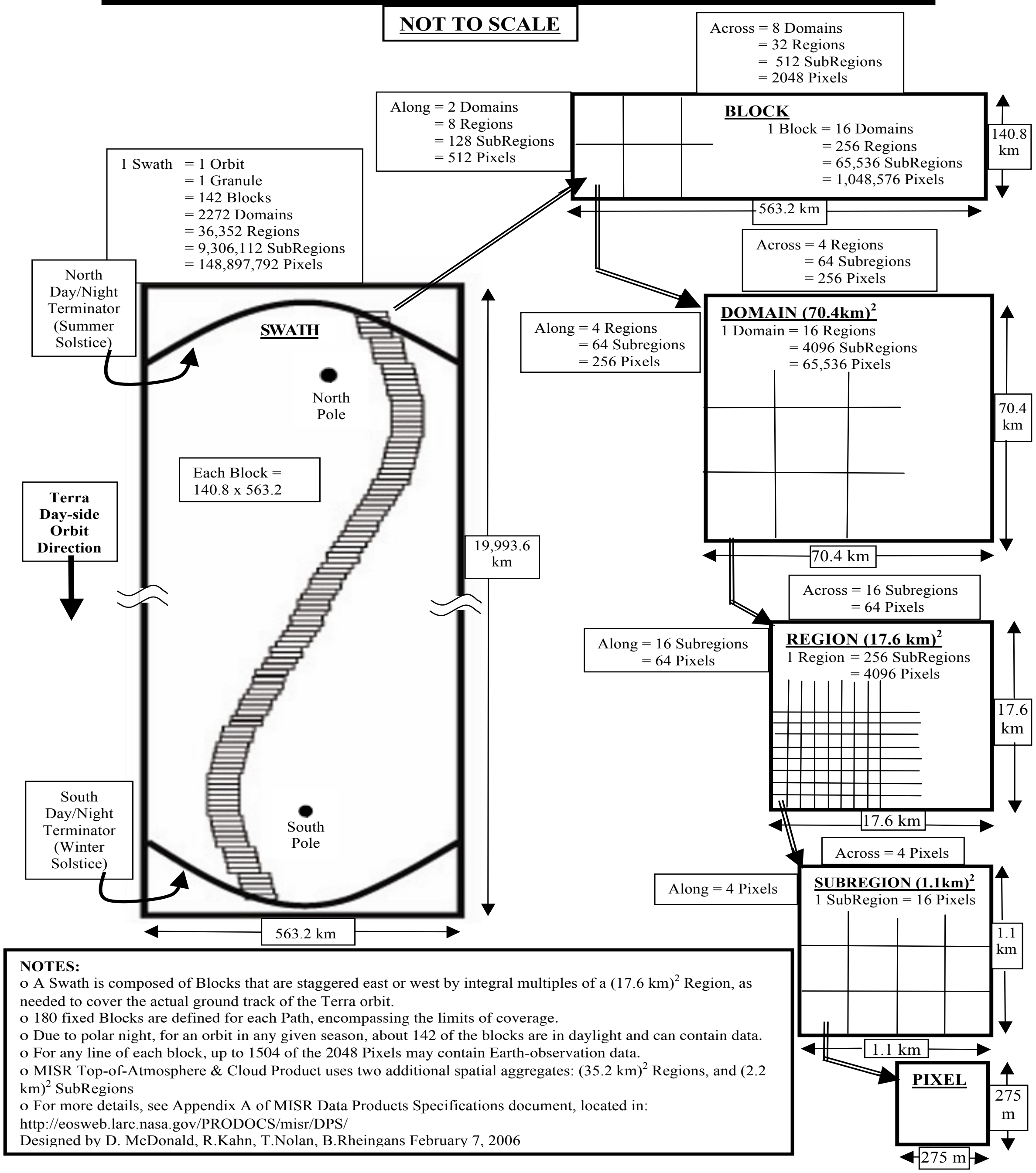
http://eosweb.larc.nasa.gov/MISRBR/





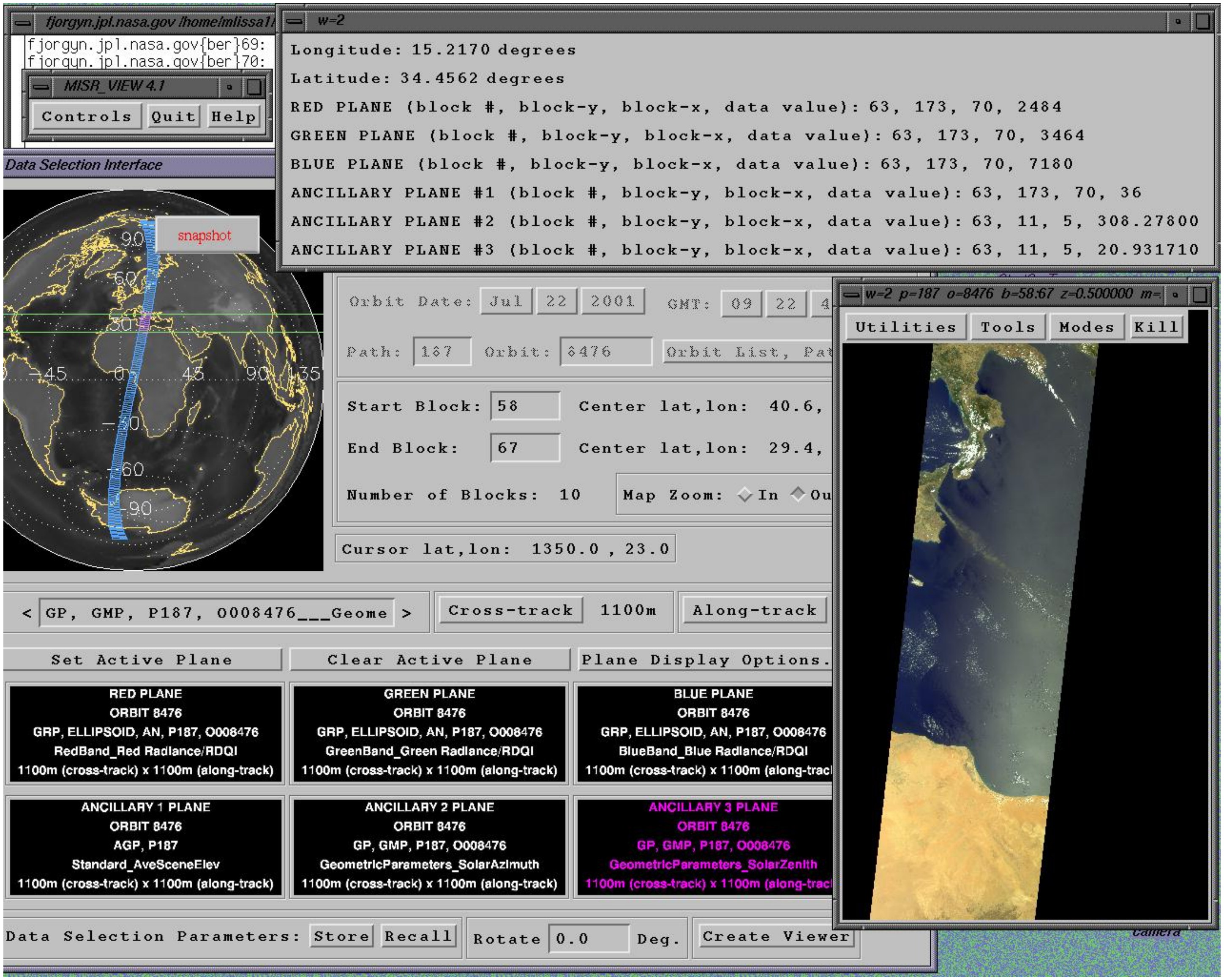


Schematic Hierarchy of MISR Aerosol-Surface Product Spatial Domains

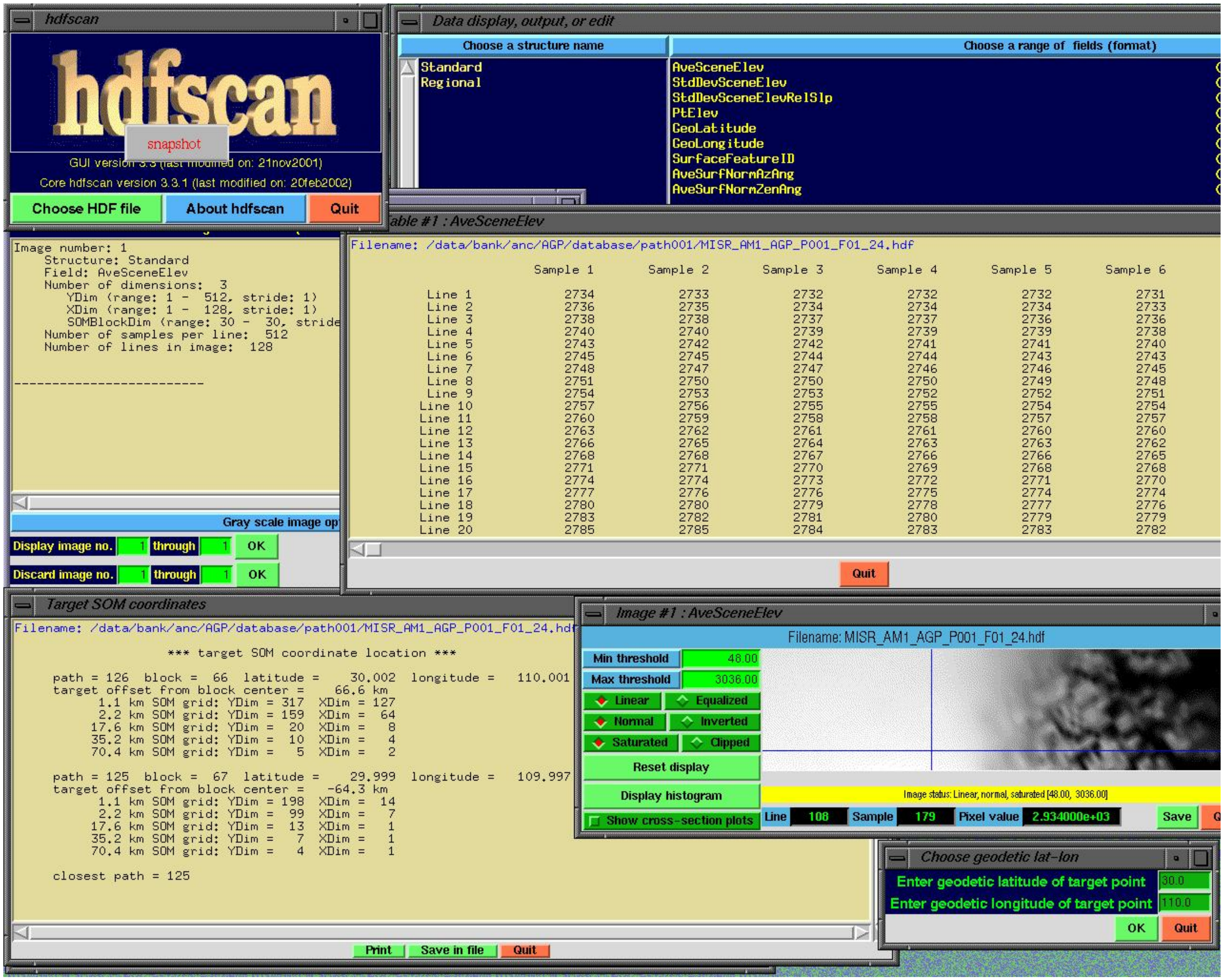


NOTES:
o A Swath is composed of Blocks that are staggered east or west by integral multiples of a $(17.6\ km)^2$ Region, as needed to cover the actual ground track of the Terra orbit.
o 180 fixed Blocks are defined for each Path, encompassing the limits of coverage.
o Due to polar night, for an orbit in any given season, about 142 of the blocks are in daylight and can contain data.
o For any line of each block, up to 1504 of the 2048 Pixels may contain Earth-observation data.
o MISR Top-of-Atmosphere & Cloud Product uses two additional spatial aggregates: $(35.2\ km)^2$ Regions, and $(2.2\ km)^2$ SubRegions
o For more details, see Appendix A of MISR Data Products Specifications document, located in:
http://eosweb.larc.nasa.gov/PRODOCS/misr/DPS/
Designed by D. McDonald, R.Kahn, T.Nolan, B.Rheingans February 7, 2006


MISR VIEW
Version 5 . 0
requires IDL 6 . 1


fjorgyn.jpl.nasa.gov /home/mlissa1/
fjorgyn.jpl.nasa.gov{ber}69:
fjorgyn.jpl.nasa.gov{ber}70:
MISR_VIEW 4.1
Controls
Quit
Help
Data Selection Interface
snapshot
w=2
Longitude: 15.2170 degrees
Latitude: 34.4562 degrees
RED PLANE (block #, block-y, block-x, data value): 63, 173, 70, 2484
GREEN PLANE (block #, block-y, block-x, data value): 63, 173, 70, 3464
BLUE PLANE (block #, block-y, block-x, data value): 63, 173, 70, 7180
ANCILLARY PLANE #1 (block #, block-y, block-x, data value): 63, 173, 70, 36
ANCILLARY PLANE #2 (block #, block-y, block-x, data value): 63, 11, 5, 308.27800
ANCILLARY PLANE #3 (block #, block-y, block-x, data value): 63, 11, 5, 20.931710
Orbit Date: Jul 22 2001
GMT: 09 22
Path: 187
Orbit: 8476
Start Block: 58
Center lat,lon: 40.6,
End Block: 67
Center lat,lon: 29.4,
Number of Blocks: 10
Map Zoom: In
Cursor lat,lon: 1350.0 , 23.0
w=2 p=187 o=8476 b=58:67 z=0.500000
Utilities
Tools
Modes
Kill
GP, GMP, P187, O008476___Geome
Cross-track
1100m
Along-track
Set Active Plane
Clear Active Plane
Plane Display Options.
RED PLANE
ORBIT 8476
GRP, ELLIPSOID, AN, P187, O008476
RedBand_Red Radiance/RDQI
1100m (cross-track) x 1100m (along-track)
GREEN PLANE
ORBIT 8476
GRP, ELLIPSOID, AN, P187, O008476
GreenBand_Green Radiance/RDQI
1100m (cross-track) x 1100m (along-track)
BLUE PLANE
ORBIT 8476
GRP, ELLIPSOID, AN, P187, O008476
BlueBand_Blue Radiance/RDQI
ANCILLARY 1 PLANE
ORBIT 8476
AGP, P187
Standard_AveSceneElev
1100m (cross-track) x 1100m (along-track)
ANCILLARY 2 PLANE
ORBIT 8476
GP, GMP, P187, O008476
GeometricParameters_SolarAzimuth
1100m (cross-track) x 1100m (along-track)
ANCILLARY 3 PLANE
ORBIT 8476
GP, GMP, P187, O008476
GeometricParameters_SolarZenith
Data Selection Parameters:
Store
Recall
Rotate
0.0
Deg.
Create Viewer


hdfscan
hdfscan
GUI version 3.3 (last modified on: 21nov2001)
Core hdfscan version 3.3.1 (last modified on: 20feb2002)
Choose HDF file
About hdfscan
Quit


hdfscan
hdfscan
snapshot
GUI version 3.3 (last modified on: 21nov2001)
Core hdfscan version 3.3.1 (last modified on: 20feb2002)
Choose HDF file
About hdfscan
Quit
Data display, output, or edit
Choose a structure name
Standard
Regional
Choose a range of fields (format)
AveSceneElev
StdDevSceneElev
StdDevSceneElevRelSlp
PtElev
GeoLatitude
GeoLongitude
SurfaceFeatureID
AveSurfNormAzAng
AveSurfNormZenAng
Image number: 1
Structure: Standard
Field: AveSceneElev
Number of dimensions: 3
YDim (range: 1 - 512, stride: 1)
XDim (range: 1 - 128, stride: 1)
SOMBlockDim (range: 30 - 30, stride
Number of samples per line: 512
Number of lines in image: 128
Gray scale image op
Display image no. 1 through 1 OK
Discard image no. 1 through 1 OK
able #1 : AveSceneElev
Filename: /data/bank/anc/AGP/database/path001/MISR_AM1_AGP_P001_F01_24.hdf
Sample 1 Sample 2 Sample 3 Sample 4 Sample 5 Sample 6
Line 1 2734 2733 2732 2732 2732 2731
Line 2 2736 2735 2734 2734 2734 2733
Line 3 2738 2738 2737 2737 2736 2736
Line 4 2740 2740 2739 2739 2739 2738
Line 5 2743 2742 2742 2741 2741 2740
Line 6 2745 2745 2744 2744 2743 2743
Line 7 2748 2747 2747 2746 2746 2745
Line 8 2751 2750 2750 2750 2749 2748
Line 9 2754 2753 2753 2752 2752 2751
Line 10 2757 2756 2755 2755 2754 2754
Line 11 2760 2759 2758 2758 2757 2757
Line 12 2763 2762 2761 2761 2760 2760
Line 13 2766 2765 2764 2763 2763 2762
Line 14 2768 2768 2767 2766 2766 2765
Line 15 2771 2771 2770 2769 2768 2768
Line 16 2774 2774 2773 2772 2771 2770
Line 17 2777 2776 2776 2775 2774 2774
Line 18 2780 2780 2779 2778 2777 2776
Line 19 2783 2782 2781 2780 2779 2779
Line 20 2785 2785 2784 2783 2783 2782
Quit
Target SOM coordinates
Filename: /data/bank/anc/AGP/database/path001/MISR_AM1_AGP_P001_F01_24.hdf
*** target SOM coordinate location ***
path = 126 block = 66 latitude = 30.002 longitude = 110.001
target offset from block center = 66.6 km
1.1 km SOM grid: YDim = 317 XDim = 127
2.2 km SOM grid: YDim = 159 XDim = 64
17.6 km SOM grid: YDim = 20 XDim = 8
35.2 km SOM grid: YDim = 10 XDim = 4
70.4 km SOM grid: YDim = 5 XDim = 2
path = 125 block = 67 latitude = 29.999 longitude = 109.997
target offset from block center = -64.3 km
1.1 km SOM grid: YDim = 198 XDim = 14
2.2 km SOM grid: YDim = 99 XDim = 7
17.6 km SOM grid: YDim = 13 XDim = 1
35.2 km SOM grid: YDim = 7 XDim = 1
70.4 km SOM grid: YDim = 4 XDim = 1
closest path = 125
Print
Save in file
Quit
Image #1 : AveSceneElev
Filename: MISR_AM1_AGP_P001_F01_24.hdf
Min threshold 48.00
Max threshold 3036.00
Linear
Equalized
Normal
Inverted
Saturated
Clipped
Reset display
Display histogram
Show cross-section plots
Image status: Linear, normal, saturated [48.00, 3036.00]
Line 108 Sample 179 Pixel value 2.934000e+03
Save
Choose geodetic lat-lon
Enter geodetic latitude of target point 30.0
Enter geodetic longitude of target point 110.0
OK
Quit

MISR Level 2 Aerosol Product – Key Fields

RegBestEstimate**SpectralOptDepth** – 4 values, the mean of all successful models in the climatology
RegBestEstimate**SpectralOptDepthUnc** – 4 values, standard deviation of all successful models
RegBestEstimate**AngstromExponent** – slope of linear least-squares fit to log AOTs vs. log of four wavelengths
RegBestEstimate**SpectralSSA** – aggregated among successful models by binning rules
RegBestEstimateSpectral**OptDepthFraction** -- AOT fraction grouped by (1) rad < 0.35; (2) 0.35 < rad < 0.7; (3) rad > 0.7; (4) spherical; (5) non-spherical
RegBestEstimate**NumberFraction** – five fractional values, based on relative particle number concentration
RegBestEstimate**VolumeFraction** – five fractional values, volume-weighted
RegBestEstimate**QA** – 0=1 successful mixture; 1= (>1) successful mixtures; 2=not used; 3=no successful mixtures
Reg**LowestResidSpectralOptDepth**, etc. – value for mixture having lowest ChiSqAbs or ChiSqHet

AlgTypeFlag – gives the algorithm type used for the region: 1=dark water; 3=het. land, 253=fill
RegClassInd – 0=clear; 1=solar oblique; 2=topo. complex; 3=cloudy; 4=no data; 253=fill
AerRetrSuccFlag – 1=no successful mixtures; 3=algorithm failure; 5=insufficient data; 7=successful retrieval
NumSuccAerMixture – number of successful mixtures
NumCamUsed – number of cameras with good data and not in glint (max=9)
NumAcceptSubr – number of 1.1 km sub-regions within region passing all criteria for use (max=256)
RegEqRefl – observed regional equivalent reflectances used in retrieval (max=36)
SolZenAng, **ScatterAng**, **GlitterAng**, etc. – region-specific geometry
AerRetrSuccFlagPerMixture – 1=mixture successful; 251, 252, 253=mixture not successful
OptDepthPerMixture – lowest resid. AOT for each mixture, successful **or not**. (V15 max=24; V16 max=74)
ChisqAbs, Geom, Spec, Maxdev, Het – per mixture ChiSq values, whether the mixture was successful **or not**

RetrAppMask (**Subreg**ParamsAer) – 0=clear; 1=missing data; 2=poor quality; 7=cloudy, etc.

Reference: MISR **Data Product Specification** document, Section 8: Level 2 Aerosol/Surface Product

MISR Level 2 Aerosol Product – Additional Files Needed for Some Applications

- **ACP** (**Aerosol Climatology Product**)

  -- **APOP** – Aerosol Physical and **Optical Properties** table – 8 Components (V16)

  -- Aerosol **Mixture File** – Up to three-component mixtures (74 in V16; 24 in V15)

- **AGP** (**Ancillary Geographic Product**)

  -- One for each of 233 SOM "Paths," 1.1 km resolution

  -- Pixel lat, long, surface type, elevation

- **ARP** (**Ancillary Radiometric Product**)

  -- Pre-flight & in-flight radiometric calibration parameters, spectral band passes

  -- Scale Factors to convert unpacked DN into Radiance (W/m2-str-micron)

Reference: MISR **Data Product Specification** doc, Section 9. MISR Ancillary Products

Most key aerosol quantities are **also stored in Aerosol Product metadata**

Some Satellite-Aerosol-Product-Related Web Sites

- http://earthobservatory.nasa.gov NASA **Earth Observatory** Imagery, Captions, Features
- https://worldview.earthdata.nasa.gov **Worldview Data Display** Website (MODIS, VIIRS)
- http://daac.gsfc.nasa.gov/giovanni/ **Giovanni** on-line visualization & analysis tools
- http://neo.sci.gsfc.nasa.gov **NASA Earth Observations** Website
- https://lance.modaps.eosdis.nasa.gov/realtime/2008031/ MODIS **Near-Real-Time Imagery**
- https://earthdata.nasa.gov/earth-observation-data/near-real-time/download-nrt-data
  Near-Real-Time MODIS, MISR, AIRS, AMSR2, MLS, OMI, VIIRS data
- http://rapidfire.sci.gsfc.nasa.gov/ **MODIS** rapid response imagery
- http://www.goes.noaa.gov/#main-content NOAA **GOES Geostationary Imagery**
- http://cloudsgate2.larc.nasa.gov/index.html NASA Langley Satellite **Imagery & Cloud** Data
- http://cloudsgate2.larc.nasa.gov/cgi-bin/predict/predict.cgi Satellite **Overpass Predictor**
- http://disc.sci.gsfc.nasa.gov/acdisc/TOMS/tomsl3_dataset.gd.html TOMS **O_3, Gases, Arsls**
- http://www.ssd.noaa.gov/PS/FIRE/GASP/AOD/ NOAA **MODIS AOD** Maps
- http://neo.sci.gsfc.nasa.gov **CALIPSO Browse** Imagery

Some Satellite-Aerosol-Product-Related Web Sites

- http://eosweb.larc.nasa.gov **MISR, CERES, SAGE**, MOPITT, TES, data & docs
- http://www-misr.jpl.nasa.gov **MISR** Home page; background, image gallery,..
- http://modis-atmos.gsfc.nasa.gov/IMAGES/index.html **MODIS** global browse imagery
- http://modis-atmos.gsfc.nasa.gov/ **MODIS** atmosphere products & docs
- http://ncc.nesdis.noaa.gov/VIIRS/ NOAA **VIIRS** data & docs
- http://www-modis.bu.edu/ **MODIS** land cover, surface albedo, and BRDF products
- http://modis-fire.umd.edu/ MODIS-UMD **Fire products** & docs
- http://activefiremaps.fs.fed.us/activefiremaps.php MODIS global **Fire occurrence mapper**
- http://www.star.nesdis.noaa.gov/smcd/spb/aq/ IDEA merged MODIS-EPA **Air Quality**
- http://alg.umbc.edu/usaq/ UMBC **Air Quality** events
- http://oceancolor.gsfc.nasa.gov/SeaWiFS/BACKGROUND/ **SeaWiFS** data & docs
- http://aeronet.gsfc.nasa.gov/ **AERONET** AOT & properties, data & docs
- http://mplnet.gsfc.nasa.gov **MPLNET** Micro-pulse LIDAR data & docs

Using *In Situ* Observations
To Add Value to Satellite Data

SAM-CAAM

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

[This is currently a ***concept-development effort***, not yet a project]

***Primary Objectives*:**

- **Interpret and *enhance 16+ years of satellite aerosol retrieval* products**
- ***Characterize statistically particle properties* for major aerosol types globally, to provide detail unobtainable from space, but needed to *improve*:**

-- Satellite aerosol *retrieval algorithms*

-- The *translation between satellite-retrieved aerosol optical properties and* species-specific aerosol mass and size tracked in *aerosol transport & climate models*

Kahn et al., BAMS submitted

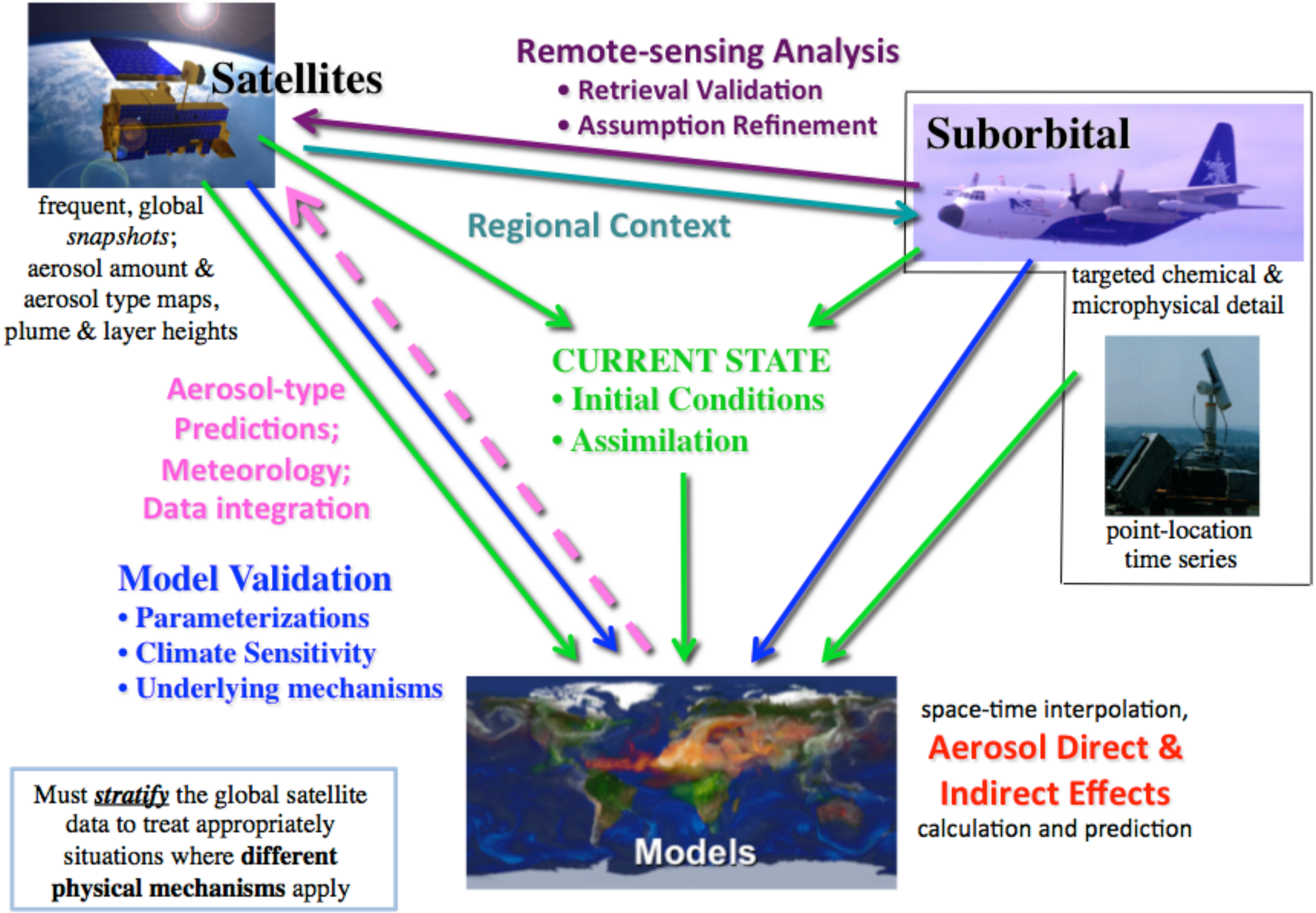
SAM-CAAM *Concept*

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

- ***Dedicated Operational Aircraft*** – routine flights, 2-3 x/week, on a continuing basis
- ***Sample Aerosol Air Masses*** accessible from a given base-of-operations, then move; project science team to determine schedule, possible field campaign participation
- Focus on *in situ* ***measurements required*** to characterize particle ***Optical Properties***, ***Chemical Type***, and ***Mass Extinction Efficiency*** (MEE)
- ***Process Data Routinely*** at central site; instrument PIs develop & deliver algorithms, upgrade as needed; data distributed via central web site
- Peer-reviewed Paper identifying ***4 Payload Options***, of varying ambition; subsequent selections based on agency buy-in and available resources

SAM-CAAM is feasible because:
Unlike aerosol amount, ***aerosol microphysical properties tend to be repeatable*** from year to year, for a given source in a given season

Kahn et al., BAMS submitted



Adapted from: Kahn, Survy. Geophys. 2012

Backup Slides

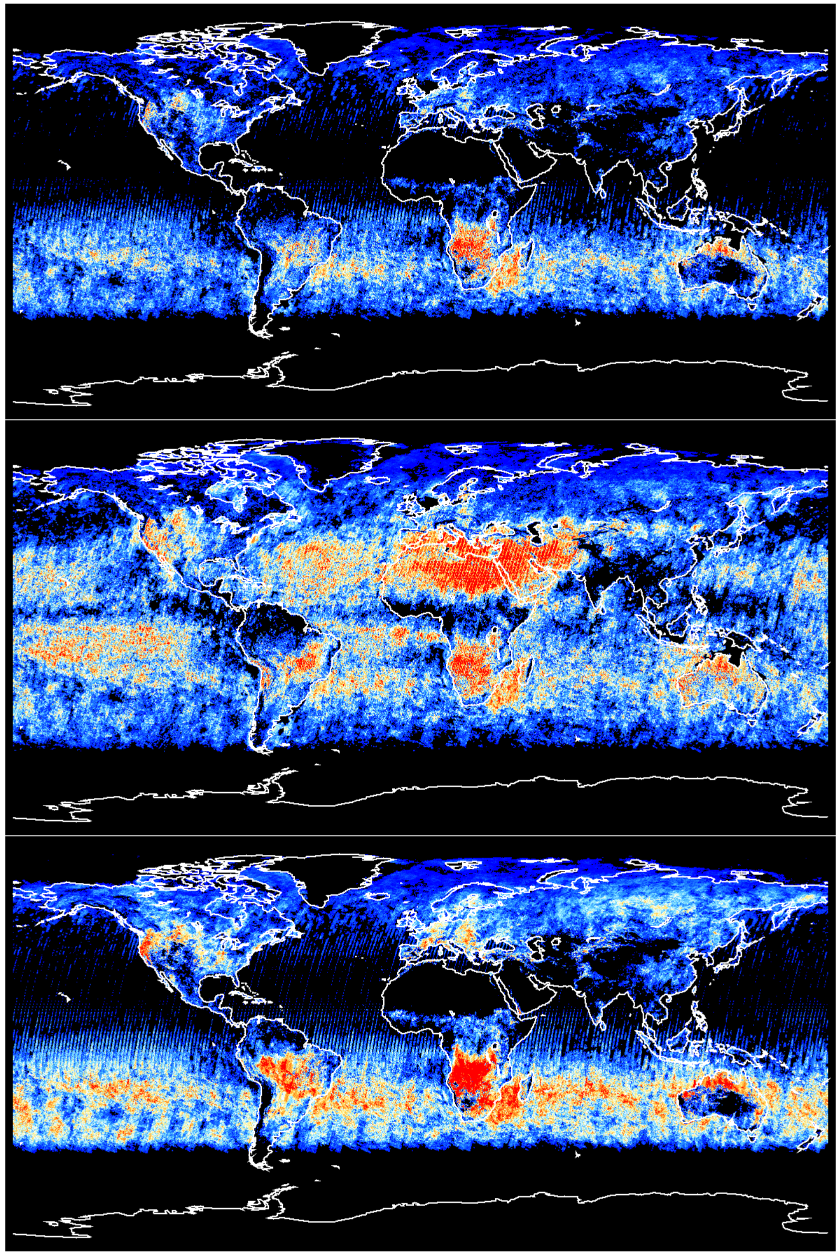
Global Distribution of MISR & MODIS *Coincident*, Retrieved AOD

Overall, **6% to 7%** of overlapping observations produce ***coincident***, MISR & MODIS aerosol retrievals

Some coincident coverage over much of the planet

Point density varies

- Desert
- Snow & Ice
- Cloud
- Polar night
- Glint



July 2006

Matched MISR/MODIS

Percent Coverage

0% 50% 100%

MISR Only

MODIS Only (*within* MISR swath)

Kahn, Nelson, Garay et al., TGRS, 2009